OMNI-DIRECTIONAL INSECT EYE CONCENTRATOR USING A HYPER-SPECTRAL PHOTOVOLTAIC CAVITY CONVERTER

FEASIBILITY ANALYSIS AND FINAL EISG REPORT

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California Energy Commission
Energy Innovations Small Grant Program

Prepared By:
Dr. Ugur Ortabasi
United Innovations Inc.

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ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

FEASIBILITY ANALYSIS REPORT (FAR)

OMNI-DIRECTIONAL INSECT EYE CONCENTRATOR USING A HYPER-SPECTRAL PHOTOVOLTAIC CAVITY CONVERTER

EISG AWARDEE
UNITED INNOVATIONS, Inc.
1782 La Costa Meadows Drive, Suite 102
San Marcos, CA 92069
Phone: (760) 744 2575
Email: uortabasi@unitedinnovations.com
Principal Investigator: Dr. Ugur Ortabasi

AUTHOR
EISG Program Administrator

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LEGAL NOTICE

PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million of which $2 million/year is allocated to the Energy Innovation Small Grant (EISG) Program for grants. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University, which is under contract to the Commission.

The EISG Program conducts four solicitations a year and awards grants up to $75,000 for promising proof-of-concept energy research.

PIER funding efforts are focused on the following six RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent Assessment
- Appendices
    - Appendix A: Final Report (under separate cover)
    - Appendix B: Awardee Rebuttal to Independent Assessment (Awardee option)

For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission's Web site at:
http://www.energy.ca.gov/research/innovations

or contact the EISG Program Administrator at (619) 594-1049 or email
eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at
http://www.energy.ca.gov/research/index.html.

Omni-Directional Insect Eye Concentrator Using A Hyper-Spectral Photovoltaic Cavity Converter

EISG Grant # 00-13

Awardee:	UNITED INNOVATIONS, Inc.
Principal Investigator:	Dr. Ugur Ortabasi
PI contact Info:	Phone (760) 744-2575; email:uortabasi@unitedinnovations.com

Grant Funding:	$74,992
Grant Term:	February 2001 – January 2002

Introduction

California's potential to generate electricity using solar photovoltaic (PV) technology is enormous. High first cost continues to limit rapid deployment of this technology. It is very important to reduce the consumer's first cost of solar electricity (currently around $6/W installed) to encourage greater deployment of solar PV generation. In addition, recent legislation demands that investor-owned utilities provide 20% of their power from renewable sources by 2017.

The objective of this project was to develop a low-cost solar photovoltaic concentrator to achieve solar concentrations of 50 suns. The solar collector was modeled on omni-directional insect eye optics. Minimal tracking requirements were anticipated. The researcher projected the new solar concentrator optics would require fewer highly efficient solar cells than non-concentrating systems. This could mitigate the otherwise unacceptably high cost of current efficient cells. The associated receiver optical system is much less expensive than the solar cell materials it would replace. The researcher projected a reduction in cost for PV systems to less than $3/watt upon successful completion of this project. The proposed concept combined omni-directional "insect eye" optics with a photovoltaic cavity converter (PVCC). A spectral splitting process inside the PVCC used Rugate filters deposited on high-efficiency solar cells to maximize the use of the available solar spectrum and to boost conversion efficiency. Commercial and residential rooftop applications are the anticipated final target of this project.

The PVCC module contained an array of discrete concentration/conversion units that operated independently. These units were electrically connected in series and in parallel to achieve the required open-circuit voltage and short-circuit current for the module. Each unit had upward-looking multi-facetted optics that resembled the compound eye of an insect. Each individual facet concentrated the solar flux and injected it into a spherical cavity shared by all facets in the PVCC module. The assembly of the facets collectively provided a large acceptance angle for each insect eye that minimized or eliminated tracking requirements. The spherical cavity (PVCC) contained the cells that were attached to its interior surface. The PVCC trapped the concentrated light it received from all facets in that unit and split the solar spectrum into discrete frequency bands. The cells inside the cavity consisted of four different groups, all from the III-V family. The spectral response of each group is different, but together they span the solar spectrum. Each cell group was covered with a conjugate Rugate filter that screened the photons, so that the photons with matching energy (frequency) passed directly to the detector, and the remainder were reflected. This "spectral screening" process inside the cavity optimized the conversion efficiency, as it allows the photons to be captured in the proper cells with full utilization of the solar spectrum.

Objective

The objective of this project was to prove the feasibility of using multi-faceted optics as a solar concentrator and an optical cavity containing multiple, spectrally selective (Rugate) filters to economically capture portions of the solar energy, sending each portion to a detector tailored to a specific frequency range. The overall goal was to develop a solar energy conversion device with very high efficiency and low cost. To accomplish this goal the researcher established the following objectives:

1. Create an optical system with a Photon Utilization Factor (PUF) in the cavity greater than 0.9. The PUF is the probability of a photon entering the cavity to be captured in a matching converter cell.
2. Select four candidate materials from those in the III-V group that span the solar spectral range for the sub-cell photon converters.
3. Achieve composite field of view of +/- 30 degrees and light throughput efficiency of the facetted insect eye optics of at least 80%.
4. Achieve solar flux concentration ratio inside the cavity greater than 30 suns.
5. Determine the optimum operational cell temperature.
6. Achieve overall performance of the proposed system of >38% @ 25^o C.
7. Develop a low-cost manufacturing process to achieve system costs of less than $3/watt.

Outcomes

1. The researcher measured the Photon Utilization Factor (PUF) in the cavity at 0.806.
2. The researcher identified four candidate materials (III-V) for the sub-cells: InGaP, GaAs, InGaAsP, and InGaAs. Their transmission frequency bands are, respectively, 350-650 nm, 650-850 nm, 850-1050 nm, and 1050-1800 nm.
3. Maximum composite field of view was +/- 30 degrees off normal. Light throughput efficiency of the facetted (insect eye) optics was 63%.
4. Highest solar flux concentration ratio inside the cavity was just over one tenth of a sun, that is, it was 0.11 suns.
5. The researcher determined the operational cell temperature to be 65^0 C @ 25^0 C and 50 suns.
6. The researcher calculated the overall performance of the system at 22.27 % @ 25^0 C and 50 suns.
7. The researcher provided insights into potential low-cost manufacturing steps for the system. They included nickel electroforming for the faceted optics. For the cavity, the researcher suggested spin forming of aluminum.

Conclusions

1. While not meeting the stated objective, the researcher was successful in achieving relatively high PUF.
2. The researcher identified four materials that span the spectral range necessary to achieve high photon-conversion efficiencies.
3. The researcher met this stated objective for the optical field of view.
4. The maximum solar concentration achieved was vastly lower than the objective. This discrepancy was caused by a physical mismatch of the concentrating optics and the receiver

cavity. Continuing R&D to achieve the objective of 30 to 50 sun concentration would be considered high risk R&D.

5. The researcher met his stated goal of determining the optimum operational cell temperature.
6. The overall system performance was impaired by the lack of solar concentration. Calculations showed that the photovoltaic converter cavity with the four sub-cells could operate at a cavity efficiency of 47%. The researcher also calculated the efficiency for a total solar system using his photovoltaic cavity converter and a tracking dish concentrator at 38%. If this efficiency could be achieved in practice it would be a major success.
7. Without the benefit of multifaceted optical concentrators, no savings in system cost could be realized. Therefore, the cost of solar electricity could not be reduced with the proposed system. However, there remains the potential that the revised system using a tracking dish concentrator could provide highly efficient and economical solar-derived electricity.

Overall this project did not prove the feasibility of the proposed system as a whole. However, the PVCC unit that converts the concentrated solar energy into electricity worked quite well. Unfortunately the extremely low concentration caused by a geometrical (structural) constraint in the design of the facetted optics represents a major problem. In his final report the researcher proposed coupling his successful, photovoltaic cavity converter to a tracking dish concentrator. The PA concludes that this could be highly successful.

Benefits to California

Concentrating solar systems have the potential to provide significant benefits to the ratepayers of California. However the multifaceted optical concentrator in this project did not provide the desired solar concentration. The selective filter receiver (PVCC) may have benefits if coupled to a more effective concentrator. Quantifiable benefits can only be determined once that system is designed and demonstrated.

Recommendations

The extensive R&D required to resolve the problems involving the facetted optics represent too high a risk and should not be pursued. However, the valuable PVCC knowledge obtained in this project could be used in conjunction with a parabolic dish concentrator to form a Dish/ PVCC system. Such a system circumvents the problem of low concentration in the facetted optics and allows the PVCC conversion approach to reach higher performance. The researcher has received additional funding from a federal agency to pursue that concept. The PA recommends that Californians interested in the deployment of high-efficiency solar-energy systems monitor the progress of this potentially valuable concept.

Stages and Gates Methodology

The California Energy Commission utilizes a stages and gates methodology for assessing a project's level of development and for making project management decisions. For research and development projects to be successful they need to address several key activities in a coordinated fashion as they progress through the various stages of development. The activities of the stages and gates process are typically tailored to fit a specific industry and in the case of PIER the activities were tailored to be appropriate for a publicly funded energy research and development program. In total there are seven types of activities that are tracked across eight stages of development as represented in the matrix below.

Development Stage/Activity Matrix

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Activity 1								
Activity 2								
Activity 3								
Activity 4								
Activity 5								
Activity 6								
Activity 7								

A description the PIER Stages and Gates approach may be found under "Active Award Document Resources" at: http://www.energy.ca.gov/research/innovations and are summarized here.

As the matrix implies, as a project progresses through the stages of development, the work activities associated with each stage needs to be advanced in a coordinated fashion. The EISG program primarily targets projects that seek to complete Stage 3 activities with the highest priority given to establishing technical feasibility. Shaded cells in the matrix above require no activity, assuming prior stage activity has been completed. The development stages and development activities are identified below.

Development Stages:	Development Activities:
Stage 1: Idea Generation & Work Statement Development	Activity 1: Marketing / Connection to Market
Stage 2: Technical and Market Analysis	Activity 2: Engineering / Technical
Stage 3: Research & Bench Scale Testing	Activity 3: Legal / Contractual
Stage 4: Technology Development and Field Experiments	Activity 4: Environmental, Safety, and Other Risk Assessments / Quality Plans
Stage 5: Product Development and Field Testing	Activity 5: Strategic Planning / PIER Fit - Critical Path Analysis
Stage 6: Demonstration and Full-Scale Testing	Activity 6: Production Readiness / Commercialization
Stage 7: Market Transformation	Activity 7: Public Benefits / Cost
Stage 8: Commercialization	

Independent Assessment

For the research under evaluation, the Program Administrator assessed the level of development for each activity tracked by the Stages and Gates methodology. This assessment is summarized in the Development Assessment Matrix below. Shaded bars are used to represent the assessed level of development for each activity as related to the development stages. Our assessment is based entirely on the information provided in the course of this project, and the final report. Hence it is only accurate to the extent that all current and past work related to the development activities are reported.

Development Assessment Matrix

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

The Program Administrator's assessment was based on the following supporting details:

Marketing/Connection to the Market

California's legislature has ordered investor owned utilities to deliver at least 20% renewable energy by the year 2017. Utilities must also seek reasonably priced renewable energy when meeting this mandate. This proposed high-efficiency concept offers potential to provide significant renewable energy at reasonable costs.

Major competitors in this market space are Amonix, CA and Concentrator Technologies, Inc., CA. Both companies' products offer lower potential conversion efficiency than that of the proposed UI^2 concept. Thus their potential to reduce the electricity cost is much less than UI^2's dish/PVCC concept. However both companies are at Stages 4 and 5 in the development process and are more likely to attract investors' funding or future customers' attention.

Engineering/Technical

The researcher has changed his concept and abandoned the omni-directional optics for a tracking dish concentrator. Technical analysis of the dish/PVCC concept has already been completed. The proposed dish/PVCC concept will use a large parabolic dish coupled to a PVCC to achieve solar concentrations of up to 500 suns. Expected system conversion efficiency is over 38%. UI^2 must quickly take its new concept through the RD&D process and demonstrate real economical advantages. As a small high technology company UI^2 does not have the resources to complete the planned R&D efforts and the subsequent commercialization by itself.

Legal/Contractual

All proprietary information, including technical drawings regarding the PVCC and Dish/PVCC systems, has been documented in form of a patent disclosure and submitted to a patent lawyer. The researcher claims no permits (licenses) are required for any component of the PVCC system itself and its use in conjunction with concentrator dishes.

Environmental, Safety, Risk Assessments/ Quality Plans

Quality Plans include Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety and Environmental**.** It is still too early in the development cycle of the proposed dish/PVCC to prepare the necessary plans. The researcher has identified no safety or environmental risks. The PA cautions that high levels of solar concentration may require special safety procedures for those who install, service, or work near the devices.

Strategic

This product has no known critical dependencies on other projects under development by PIER or elsewhere

Production Readiness/Commercialization

UI^2 has identified and contacted several potential partners to manufacture and to market the equipment, including SES/Boeing, SAIC, and Duke Solar. UI^2 is planning to form a partnership with one of these well-established companies for commercialization.

Public Benefits

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

This project focused on increased affordability of renewable energy. The public benefits are derived from the use of a solar concentrator and a unique multi-detector receiver cavity. Because the proposed system failed in the concentrator subsystem, it was not possible to calculate public benefits. Success in the receiver cavity provides hope of achieving the original goal of a less-than-$3/watt-installed solar system when the receiver cavity is combined with a dish concentrator.

Program Administrator Assessment

After taking into consideration: (a) research findings in the grant project, (b) overall development status as determined by stages and gates, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow-on funding within the PIER program.
Receiving follow-on funding ultimately depends upon: (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)

Appendix A to FAR 00-13

ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

EISG FINAL REPORT

OMNI-DIRECTIONAL INSECT EYE CONCENTRATOR USING A HYPER-SPECTRAL PHOTOVOLTAIC CAVITY CONVERTER

EISG AWARDEE
UNITED INNOVATIONS, Inc.
1782 La Costa Meadows Drive, Suite 102
San Marcos, CA 92069
Phone: (760) 744 2575
Email: uortabasi@unitedinnovations.com

AUTHORS

Dr. Ugur Ortabasi, Principal Investigator
C. Woody Hays, Project Manager

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Legal Notice

Inquiries related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisp@energy.state.ca.us.

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Abstract

The proposed design is a non- or minimally tracking PV concentrator module that collects direct and diffuse components of solar radiation simultaneously. This novel concept called "Omni-directional Insect Eye Concentrator" or OMNIECON combines the facetted optics of an insect eye with a Photovoltaic Cavity Converter (PVCC) that splits the solar spectrum and optimizes the use of the trapped solar energy inside the cavity. The objective of this Second Stage of the program is to develop analytical models and methods to evaluate the key components and the overall performance of OMNIECON. The outcome of the studies were: a) A four band-gap, III-V cell system consisting of GaInP, GaAs, InGaAsP and InGaAs can reach a collective cell efficiency of 43% at a concentration of 50 suns; b) A compound insect eye optics consisting of seven facets has a usable view angle of +/- 30 degrees requiring two daily and two yearly adjustments. c) Physical constraints did not allow to obtain the desired 50 sun concentration; d) At 50 suns the cell temperature stabilizes at 40 C degrees above the ambient (i.e.65^0 C) for the case PVCC is cooled passively. e) The manufacturing of OMNICON requires dramatically new processes and further studies are required. All results, except (c) are close to projected targets. At this point of development (Stage 2) project goal (c) is not achieved and further investments into insect eye optics are not recommended. It is strongly recommended however that the excellent findings under (a), (b) and (d) are adapted to a Dish/PVCC concentrator system that circumvents the problems encountered in (c) and has the potential to reduce the cost of solar electricity below \$3/Watt. If the Gate 2 decisions are favorable UI^2 is prepared to submit a proposal for Stage 3, i.e. Research and Bench Scale Testing to demonstrate the feasibility of the Dish/PVCC concept.

Key Words: Concentrating Photovoltaics, Photovoltaic Cavity Converter, Omni-directional Insect Eye Optics, Spectral Splitting, Rugate Filters, Multi-bandgap Cell Systems, Ultra high Efficiency.

Executive Summary

1. Introduction

California's potential to generate solar electricity using photovoltaic technology is enormous. There is plenty of suitable land with premium solar resources with daily incident energy yields of >7.0 kWhr/m^2/day, respectively. If only 3% of the premium land located within the regions of premium solar resource were used for solar PV plant development the output would represent over 1,050 billion kWh of electricity generation annually, essentially meeting the needs of all of the western states. Yet this boundless source of raw energy is not being utilized seriously to help California's precarious energy situation.

There are several reasons why PV technology has not taken its well deserved position as a viable energy option. Many of the political, social, historical, and educational barriers as well as illogical biases are discussed and refuted by Sheer in his recent book "Solar Manifesto". The fact remains however that solar technologies are just being introduced and all capitalization must occur now to enter the market. Unlike conventional power industry, the young solar industry does not benefit from an already amortized infrastructure. The user must carry the burden of initiation. Thus it is very important to reduce the cost of solar electricity ($/W) to the consumer, as much as possible, to encourage acceptance of solar PV.

This project involves a novel solar photovoltaic concentrator and targets the PIER subject area "Renewable Energy Technologies". The rational behind the proposed design is to utilize very high efficiency solar cells (possibly of space use origin) and mitigate their otherwise unacceptable cost [$/W] by concentrating the solar radiation. Concentrator systems in general require much smaller quantities of solar cells as compared to their flat plate counterparts. The associated receiver optics (reflective concentrator mirrors in this case) is much less expensive than the solar cell materials they replace.

Present design approach for a PV concentrator involves a non-tracking, low profile concentrator with a concentration ratio of 30-50 suns under peak conditions. Although it would be more desirable to have higher concentrations, the non- or little tracking requirement limits this potential. The proposed concept, called OMNIECON combines an omni-directional "Insect Eye" optics with a photovoltaic cavity converter (PVCC). A spectral splitting process inside the PVCC aided by Rugate filters, deposited on high efficiency solar cells, maximizes the use of the available solar spectrum and boosts the conversion efficiency.

The anticipated final product targets, among other commercial sectors, the residential rooftop applications. The unique, omni-directional insect eye optics, introduced here for the first time, extends the use of this PV concentrator technology into regions with moderate climates where the relative intensity of the diffuse radiation may be much higher than in the southwest region of the USA where the dominant component of the solar flux is direct radiation.

2. Project Objectives

The objective of this second stage phase involves the technical analysis of the proposed OMNIECON concentrator module. Many features of the underlying concept are radically new and each of them require in-depth analytical studies to explore the respective technical feasibility. Our plan to approach this multi-layered research project was to subdivide the overall task (i.e. the operation of the OMNIECON system as a whole) into critical sub-tasks identified as essential for the OMNIECON to operate.

The OMNIECON module is an array of discrete concentration/conversion units that operate independently. These units are electrically connected in series and in parallel to achieve the required open circuit voltage and short circuit current for the module. Each unit has upward looking multi-facetted optics that resembles the compound eye of an insect. Each individual facet concentrates the solar flux and injects it into a spherical cavity shared by all facets in a unit. The assembly of the facets collectively provides a large acceptance angle for each insect eye that minimizes or eliminates the tracking requirements The spherical cavity called Photovoltaic Cavity Converter (PVCC) contains the cells that are attached to the interior surface of the cavity wall. The PVCC traps the concentrated light it receives from all facets in that unit and splits the solar spectrum into discrete frequency bands. The cells inside the cavity consist of four different groups all from the III-V family. The spectral response of each group is different but they all together span congruently the solar spectrum. Each cell group is covered with a conjugate Rugate filter that screens the photons. In other words photons with matching energy (frequency) are permitted and the rest reflected. This "spectral screening" process inside the cavity optimizes the conversion efficiency as it allows the photons to be captured in the proper cells and the solar spectrum is fully utilized.

The specific seven (7) sub-task objectives of this phase involved the development of analytical models and respective metrics to critically evaluate the following key parameters that are measurable: 1) Photon Utilization Factor (PUF) in the cavity; 2) Selection of four candidate III-V sub-cells; 3) Maximum Composite field of view and light throughput efficiency of the facetted insect eye optics; 4) Highest achievable solar flux concentration ratio inside the cavity; 5) Operational Cell temperature; 6) Overall performance of OMNIECON and 7) Outline of a low cost manufacturing processes.

3. Project Outcomes

The outcome of our analytical studies for the Sub-tasks 1 through 7 were:

1) Photon Utilization Factor (PUF) in the cavity; Outcome: PUF = 0.806;
2) Selection of four candidate III-V sub-cells; Outcome: GaInP, GaAs, InGaAsP and InGaAs
3) Maximum Composite field of view and light throughput efficiency of the facetted insect eye optics; Outcome: +/- 30 degrees off-normal and 63%, respectively.
4) Highest achievable solar flux concentration ratio inside the cavity; Outcome: CR = 0.11 suns
5) Operational Cell temperature; Outcome: $T_{op} = 65^0$ C @ 25^0 C T_{amb} and 50 suns
6) Overall performance of OMNIECON; Outcome: 22.27 % @ 25^0 C t_{amb} and 50 suns
7) Outline of a low cost manufacturing processes; Outcome: Facetted Inst Eye: Nickel Electroforming and Cavity: Spin Forming of Aluminum.

4. Conclusions

For the sake of brevity we list our conclusions for different subtasks in Table 1 below:

Note: The risk factors quoted below are based on a 0 to 100 scale. Increasing numbers mean increased risk of the associated R&D.

Table 1.
Overview of Project Outcomes and Risk Assessment

Sub-task No.	Measurable Parameter	Technical Objective	Results of Technical Analysis	Risk Factor (RF) and Conclusions (C)
1	Photon Utilization Factor	0.9	0.806	RF: <5 C: Successful, can be improved
2a	Selection of Candidate III-V Sub-cells	Complete Coverage of Solar Spectrum	Complete Coverage of Solar Spectrum	RF: 0 C: Highly Successful
2b	Broadband Transmission and Reflection Characteristics of Rugate Filters	Trans. ~ 99% Refl.~99%	Trans. ~ 99% Refl.~99%	RF: 0 C: Highly Successful
2c	Collective Cell Efficiency	45%	43%	RF: <5 C: Successful, can be improved
3a	Useful Field of View Angle	-30^0 to $+30^0$	-30^0 to $+30^0$	RF: 0 C: Successful, 2 adjustments per year and per day
3b	Optical Through-put of the Insect Eye at normal incidence	Single Facet: 90% Complete Eye:80%	Single Facet: 87.2 % Complete Eye: 63 %	RF(Single Facet): 0 C(Single Facet): Successful RF(Complete Eye): 80 , C(Complete Eye): R&D is necessary
4	Flux Density inside the Cavity	30 to 50 suns	0.11 suns	RF: 90 C: Not successful, High risk R&D necessary
5	Operational Cell Temperature	55^0 C to 65^0 C @ $T_a= 25^0$ C	65^0 C @ $T_a= 25^0$ C	RF: 0 C: Successful
6	Collective Module Efficiency	> 38 % @25^0C	22.27% @ 25^0 C 19.87 %@ 65^0C	RF: 50 C: Good Performance, needs R&D
7	Manufacturing	Cost effective Manufacturing Processes	Cavity: Spin Forming, Facet Optics: Electro-Forming,	RF: 80 C: No existing experience in Solar field, Needs R&D

5. Recommendations

With the exception of Sub-task 4 the project can be considered successful. The PVCC unit which converts the concentrated solar energy into electricity works extremely well. Unfortunately the extremely low concentrations caused by the geometrical (structural) constraint in the design of the insect eye optics represents a major problem as high concentration is a major requirement for this particular project to be successful. Without the benefit of high concentration no savings in cell costs can be realized and therefore the electricity cost cannot be reduced. This remains true in spite of the extremely high collective cell conversion efficiency of the PVCC and the omni-directional power collection capability of the multi-facetted insect eye. In UI^2's opinion the extensive R&D which is required to resolve the problems (involving Facetted Insect Eye Optics), represent too high a risk and should not be pursued. Instead we strongly recommend that the valuable PVCC knowledge obtained in Stage 2 is used in conjunction with a parabolic dish concentrator to form a Dish/ PVCC system described in Appendix I. Such a system circumvents the problem of low concentration and the PVCC conversion approach reaches its maximum potential. This recommendation is in full concurrence with our wish to make the best use of the already incurred investments and efforts by the Energy Commission and also by our company. UI^2 is prepared to continue with the 3^{rd} Stage of this project to develop the Dish/PVCC system.

6. **Public Benefit to California**

The statements below are based of our knowledge on the high concentration Dish/PVCC system that promises a far superior performance than any existing PV concentrator technology.
We predict that the proposed high concentration Dish/PVCC will achieve a system efficiency in excess of 38% and will bring down the cost of solar electricity to $1-3/Watt. This concentrator technology is highly suitable for California and particularly for the southwest regions of California where direct solar radiation is abundant. The following benefits will be the result of full scale commercialization of UI^2's Dish/PVCC system:

- Energy Security: Domestically produced energy decreases reliance on fuel sources outside US borders and promotes energy independence, thus increasing energy security.
- Employment: A greater fraction of HCPV energy costs are manpower related than for fossil fuels; there are thus more jobs per kilowatt-hour of output than for fossil powered plants. (For example at $3/Watt a 1000MW plant will create 10,000 high value added jobs).
- Environment: HCPV plants are environmentally friendly and produce no emissions. Thus the "external costs" like health related costs to the public, associated with the fossil powered plants are avoided.
- Export: Successful penetration into U.S. markets translates into strong export potential where competing energy costs are often higher.

Based on the foregoing national and State benefits result if HCPV can be established as a viable contributor to national and State energy needs. Realization of the benefits hinges on the potential for the HCPV success in transiting the R&D and market entry stages to a sustaining commercial status.

Introduction

California's potential to generate solar electricity using photovoltaic technology is enormous. There is plenty of suitable land with premium, excellent and good solar resources with daily incident energy yields of >7.0, 6.5-7.0 and 6.0-6.5 kWhr/m2/day, respectively. If only 3% of the premium land located within the regions of premium solar resource were used for solar PV plant development the output would represent over 1,050 billion kWh of electricity generation annually, essentially meeting the needs of all of the western states (1999 annual consumption: 1,100 billion kWhr). Yet, this boundless source of raw energy is not being utilized seriously to help California's precarious energy situation. Present plans hastily created by the state in response to alarming power shortages and grid congestions in mid 2000 have negligible solar provisions. As most experts agree, Californian's will soon depend mostly on gas generated electricity and imported power. Thus the vulnerability to shortages, uncontrollable price hikes and severe grid congestions, as Californians experienced over the last two years, will remain.

There are several reasons why PV technology has not taken its well deserved position as a viable energy option although the Californians support the idea of having a significant solar component in our power mix. Many of the political, social, historical, social, educational barriers as well as illogical biases are discussed and refuted by Sheer in his recent book "Solar Manifesto". The fact remains however that solar technologies are just being introduced and all capitalization must occur now to enter the market. Unlike the conventional power industry, the young solar industry does not benefit from an already amortized infrastructure. The consumer must carry the burden of initiation. Thus it is very important to reduce the cost of solar electricity ($/W) to the consumer, as much as possible, to encourage acceptance of solar PV.

It is a well established fact that high solar cell conversion efficiency is the key parameter to cheaper solar electricity, provided the cost of solar modules ($\$/m^2$) can be kept as low as possible. Presently however, the cost of very high efficiency cells is prohibitively high.

This project involves a novel solar photovoltaic concentrator and targets the PIER subject area "Renewable Energy Technologies". The rational behind the proposed design is to utilize very high efficiency solar cells (possibly space solar cells) and mitigate their otherwise unacceptable cost [$/W] by concentrating the solar radiation. Concentrator systems in general require much smaller quantities of solar cells as compared to their flat plate counterparts. The associated receiver optics (reflective concentrator mirrors in this case) is much less expensive than the solar cell materials they replace.

Although concentrating photovoltaics (CPV) has been explored by independent researchers and entrepreneurs on a small scale it has never been a part of any substantial, long lasting programs at the Department of Energy, except for a brief period in the late 80's at the Sandia Laboratories in Albuquerque, NM. Very recently, High Concentration Photovoltaics (HCPV) has been strongly recommended by an independent Peer Review Panel to be added to the Scope of DOE's Concentrating Solar Power (CSP) Program, which traditionally involved only solar thermal electricity generation technologies like Dish /Sterling, Power Tower and Parabolic Troughs [2]. The reason behind this new initiative for HCPV is the emergence of extremely high efficiency cells as for example the multi-junction cells (~ 34% @ 400 suns) originally developed for space. As discussed before these otherwise unacceptably expensive cells can be made very affordable for terrestrial applications by using high concentrations. The effective cost of a very expensive cell such as $500/Watt, becomes approximately $1/Watt if it is used with a concentrator operating at 500 suns. Thus HCPV represents now a most promising solar PV technology that offers the potential to generate electricity at low cost and very reliably. The HCPV also increases the existing PV power generation capacity several orders of magnitude depending on the concentration ratio used.

The present design approach for a PV concentrator involves a non-tracking, low profile concentrator with a concentration ratio of 30-50 suns under peak conditions. Although it would be more desirable to have higher concentrations, the non- or little tracking requirement limits this potential as dictated by the laws of optics. The proposed concept, called OMNIECON combines omni-directional “Insect Eye” optics with a photovoltaic cavity converter (PVCC). A spectral splitting process inside the cavity aided by Rugate filters, deposited on high efficiency solar cells, maximizes the use of the available solar spectrum and boost the conversion efficiency.

The anticipated final product targets, among other commercial sectors, the residential rooftop applications. The unique, omni-directional insect eye optics, introduced here for the first time, extends the use of this PV concentrator technology into regions with moderate climates where the relative intensity of the diffuse radiation may be much higher than in the southwest region of the USA where the dominant component of the solar flux is direct radiation.

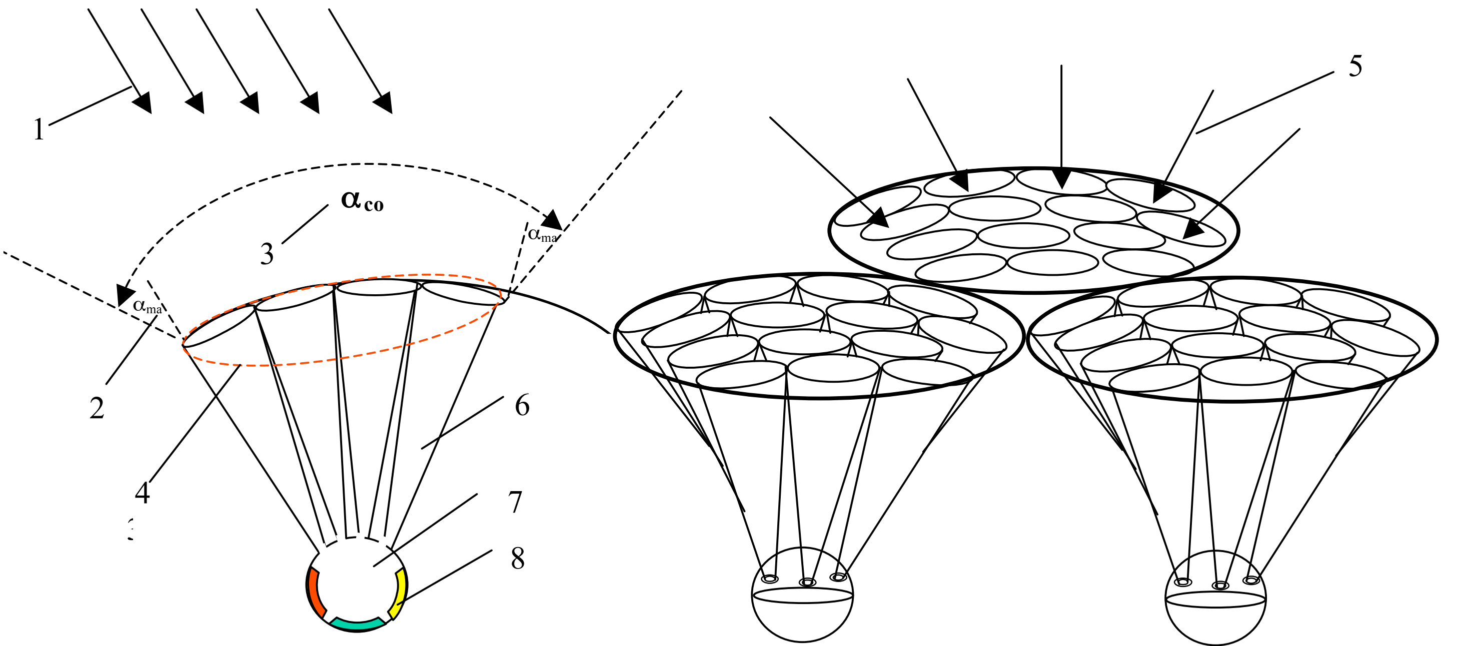
Report organization:

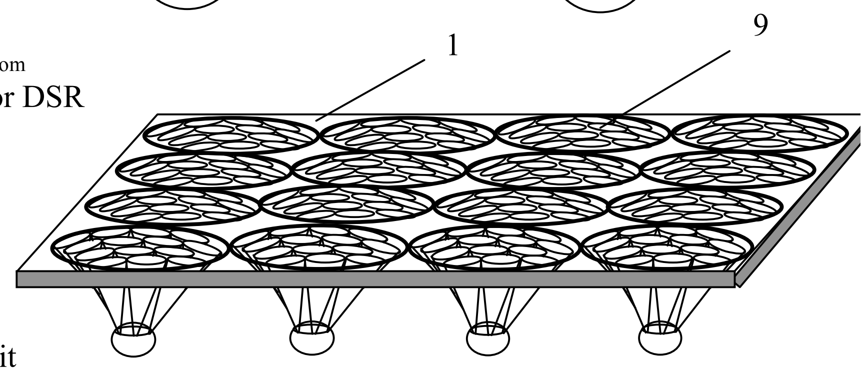
Many features of the proposed concept are radically new and each feature require in-depth analytical studies to explore their respective technical feasibility. Our plan to approach this multi-layered research project was to subdivide the overall task (i.e. the operational characteristics of the OMNIECON system as a whole) into individual sub-tasks each subtask addressing the key parameters that determine the performance of the OMNIECON. These critical sub-tasks involved cavity optics, multi-bandgap III-V solar cell systems, insect eye optics (field of view and throughput), system concentration ratio, operational cell temperature and overall system performance. Under Project Objectives, Project Approach and Project Outcome the key parameters are defined, analyzed and the findings are reported. Conclusions that follow this section are based on the outcomes and the recommendations express our vision based on the lessons learned.

Project Objectives

The objective of this second stage phase involves the modeling and analytical studies of the proposed OMNIECON concentrator module in terms of its key components that determine the overall performance of the device .

The OMNIECON module is an array of discrete units that concentrate and convert direct and diffuse solar radiation independently. These independently operating units are electrically connected in series and/or in parallel to achieve the required open circuit voltage and short circuit current for the module. Each unit has upward looking, multi-facetted optics that resembles the compound eye of an insect where each facet’s optical axis is aligned in a different direction. Each individual facet concentrates the solar flux and injects it into a spherical cavity that is shared by all facets in a unit (Figure 1). The assembly of the facets collectively provides a large acceptance angle (view angle) that minimizes or eliminates the tracking requirements. The spherical cavity called Photovoltaic Cavity Converter (PVCC) contains the cells that are attached to the interior surface of the cavity wall (Figure 2). The PVCC traps the concentrated light it receives from all facets and splits the solar spectrum into discrete frequency bands. The cells inside the cavity consist of three different groups (as example), all from the III-V family (Figure2). The spectral response of each group is different but they all together span congruently the solar spectrum. Each cell group is covered with a conjugate Rugate filter that screens the photons. In other words photons with matching energy (frequency) are permitted into the cell and the rest are reflected. This “spectral screening” process inside the cavity optimize conversion the conversion efficiency as it allows the photons to be captured in the proper cells and the solar spectrum is fully utilized.

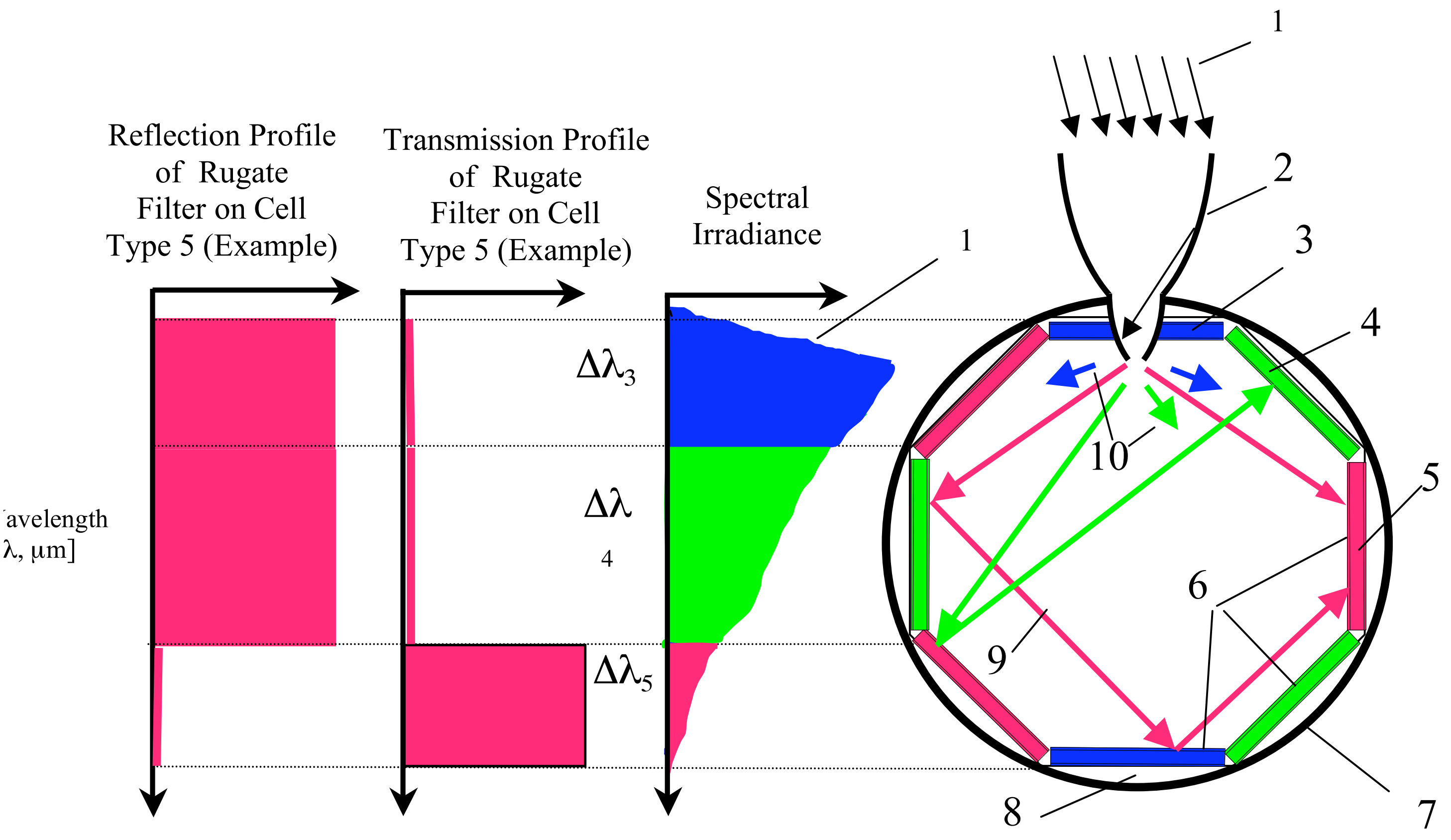




1 – Direct Solar Radiation (DSR) within α_{com}
2 – Single Facet Max. Acceptance Angle for DSR
3 – Compound Acceptance Angle
4 – Virtual Aperture
5 – Diffuse Radiation within α_{max}
6 – Single Concentrator Facet
7 – Spectral Splitting Concentrator Cavity
8 – Discrete III-V Solar Cells
9 – Compound Insect Eye Concentrator Unit
10 - Module Array

FIGURE 1. PRINCIPLES OF OMNI-DIRECTIONAL INSECT EYE CONCENTRATOR

NOT TO SCALE
CONCEPT LEVEL



Incident Solar Flux and its Spectral Distribution
Bezier Optimized Single Concentrator Facet (Reflector Type)
Discrete Cells Optimized for Spectral Window $\Delta\lambda_3$ (Cell Type 3)
Discrete Cells Optimized for Spectral Window $\Delta\lambda_4$ (Cell Type 4)
Discrete Cells Optimized for Spectral Window $\Delta\lambda_5$ (Cell Type 5)

6- Rugate Color Separation Filters on Cell Types 3,4 & 5
7- Spherical Cavity Shell
8- High Reflectivity Lining on Cavity Walls (Diffuse)
9- Random Path of a Photon within Spectral Window $\Delta\lambda_5$
10- Other Photons outside $\Delta\lambda_5$ Undergoing Spectral Splitting

FIGURE 2. PRINCIPLES OF SPECTRAL SPLITTING BY SELECTIVE TRANSMISSION AND REFLECTION IN THE INTERIOR OF OMNIECON'S CAVITY CONVERTER

Spectral screening helps also to reduce waste heat generation in the cells as most of the captured photons energy is used to create electron hole pairs to generate photocurrent.
The specific sub-task objectives of this phase involved the development of analytical models and respective metrics to critically evaluate the following key parameters that are measurable:

Sub-task 1
Determine Photon Utilization Factor (PUF) in a spherical cavity with a small entrance aperture that contains four different type of III-V cells covered with conjugate Rugate filters (Note: PUF is defined as the probability for a photon that enters the cavity to be captured by a matching cell);
Sub-task 2
a) Identify and model four candidate III-V sub-cells that form an optimal multi-bandgap PV system that will provide the highest possible collective conversion efficiency.
b) Determine transmission and reflection characteristics of conjugate Rugate filters for the selected sub-cells.
c) Determine collective solar-to-electricity conversion efficiency for a III-V multi-bandgap cell system inside a cavity with a given PUF.
Sub-task 3
a) Determine composite maximum field of view (or acceptance angle) for the omni-directional insect eye optics.
b) Determine the light throughput efficiency of the facetted insect eye optics for direct and diffuse solar radiation at different sun angles.
Sub-task 4
Determine highest achievable solar flux concentration ratio inside the cavity when the cavity is coupled to an insect eye consisting of a multiplicity of facets.
Sub-task 5
Determine operational cell temperature for a passively air cooled OMNIECON system under peak solar conditions;
Sub-task 6
Determine the overall performance of OMNIECON under simulated direct and diffuse solar radiation including diurnal and seasonal movements of the sun .
Sub-task 7
Outline of low cost manufacturing processes that will support the project performance goals.

Project Approach
Note 1: The following analytical studies described below were obtained with a cavity radius of 20 cm rather than the anticipated radius of 3 to 4 cm. This increase in diameter was imposed on the cavity model to be able to accommodate seven concentrator facets without intersection problems. The impact of this rather profound change in the design performance is discussed under the "Conclusions" section below.
Note 2: All results listed under these Sub-task assume 80% direct radiation and 20% diffuse radiation unless mentioned otherwise.
Note 3: Optical modeling of the cavity and that of the insect eye optics has been performed using ASAP ray tracing and optimization software by Breault Research. Structural modeling of the cavity was performed by using Solid Works Software. Analytical methods were used to predict the operational cell temperature. All schematics were prepared using Microsoft Power Point.

Sub-task 1
Photon Utilization Factor (PUF) is a very useful Figure of Merit that describes how efficiently the photons are utilized once they enter the cavity. In quantitative terms PUF is the probability for a photon that enters the cavity to be captured in a matching (conjugate) cell. PUF depends on the relative sizes of the cavity and entrance aperture, occupied relative cavity area by the cells and the lambertian reflector, the configuration of the cell distribution inside the cavity,

reflectance and transmittance of the Rugate Filters and the reflectance of the lambertian reflector. (Note: The shape of the cavity is also an important factor, however extensive studies we have performed has indicated that a spherical cavity yields always the highest PUF).

The optical cavity model assumes four different cell groups in agreement with the selected four III-V sub-cells. The individual cells are treated like a single detectors. Each transmitted photon adds "1" count. Each reflected photon adds "0" count. The inside of the sphere is separated into 4 detector regions (zones). The relative area occupied by each of the 4 zones is 30%, 22.5%, 22.5% and 25% for zones 1,2,3 and 4. The solar active area of each detector cell is 75%, i.e. there is a non-active area around each detector cell to allow electrical insulation of the cells from each other.

The source of radiation used in the ray tracing studies is the AM1.5 solar spectrum providing 1000W/m^2 total and 768 W/m^2 direct component. (Figure 3). According to the spectral responses of the selected cells (see Sub-task) the spectrum is divided into four frequency bands. Detector cells respond only to photons in the respective conjugate band. The Rugate filters on top of the cells are assumed to have 99% transmittance and reflectance in the prescribed portions of the solar spectrum. The diffuse reflecting lambertian cavity wall has a 99.1% reflectance. Figure 4 shows the optical model of the cavity. The sphere radius, the light entrance aperture radius and the internal cavity area are 20.0cm, 2.5cm and 5030.0cm^2, respectively. Figure 5 shows a typical ray tracing pattern for a monochromatic photon. The PUF is calculated for a statistically significant number of rays by dividing the number of counts detected by a group of cells, by the total number of conjugate photons that enter the cavity. Similar but different PUF's are calculated for each cell group and the overall PUF is calculated by taking the average of the four.

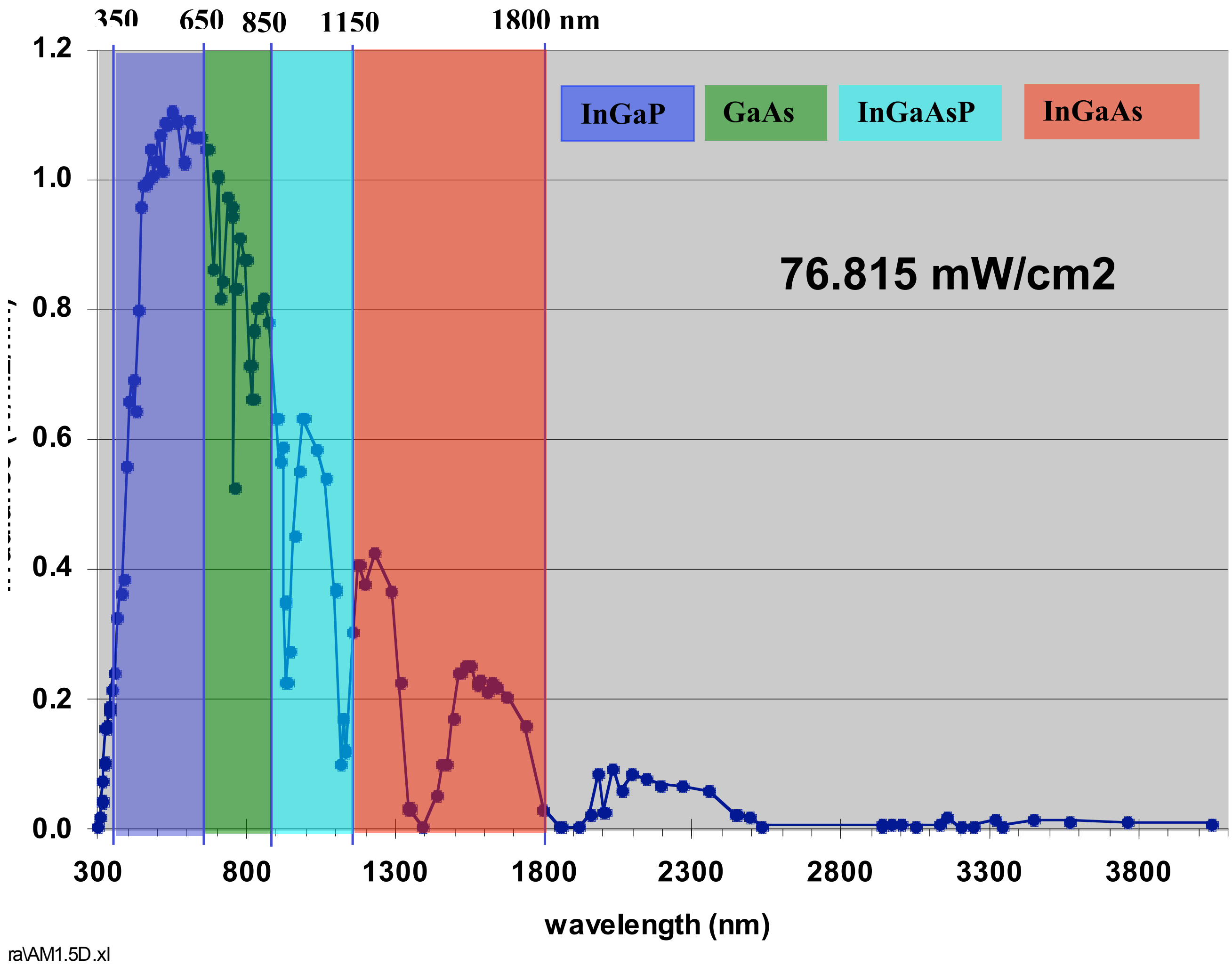


FIGURE 3. AIR MASS 1.5 SOLAR SPECTRUM AND RUGATE FILTER FREQUENCY BANDS MATCHING THE III-V CELLS

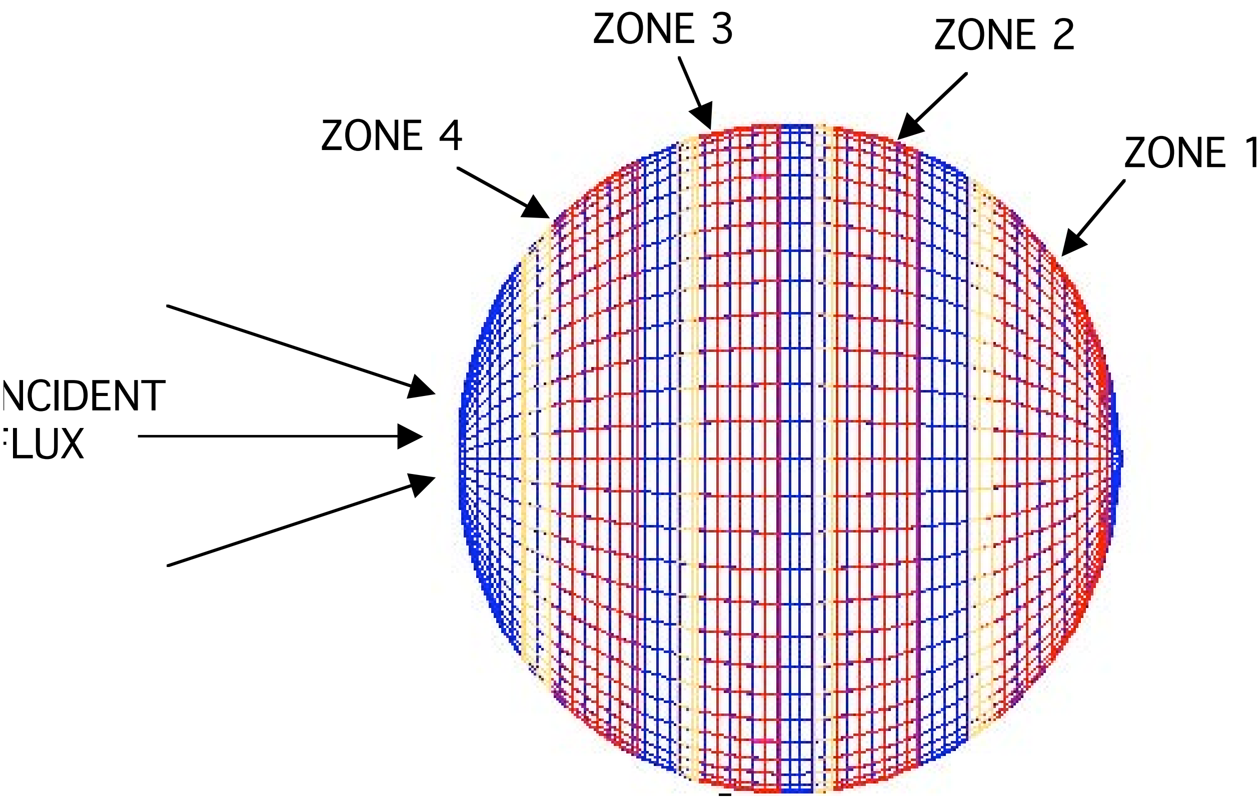


FIGURE 4. OPTICAL CAVITY MODEL SHOWING THE DISTRIBUTION OF FOUR DETECTOR CELL ZONES

Note: The four detector cell zones are indicated by red. The active portion of each zone is 75%. The blue regions are lambertian scattering zones. The reflective portion of the cells is shown in yellow.

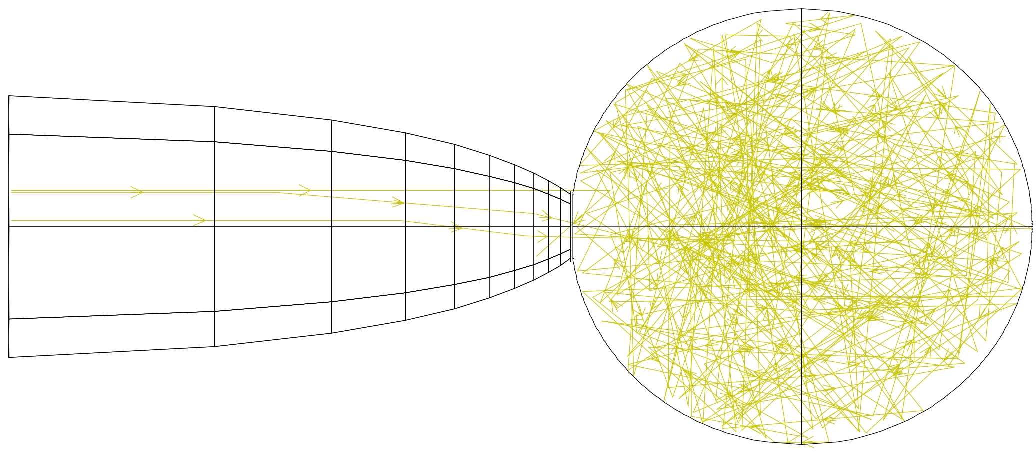


FIGURE 5. CPC CONCENTRATOR FACET ATTACHED TO LIGHT TRAPPING CAVITY AND RAY TRACING PATTERN

Monochromatic Light Incident on Optical Axis, 4 Rays are shown.

Sub-task 2a

Unlike in multi-junction cells, the sub-cell groups in a multi-bandgap system (our approach) are not affected by each other. Multijunction cells are grown (or stacked) in a vertical structure and therefore they must meet certain optical, thermal, crystalline and electronic criteria to be able to work collectively. Multi-bandgap systems as developed under this project are single-junction cells assembled in a lateral geometry and are structurally separated from each other. For this reason the availability of candidate cells to form multi-bandgap systems is much wider than in the case of multijunction cells. This feature is of great importance for cost decisions as a variety of cheaper sub-cells can be identified to achieve good performances.

For the purposes of this project we chose four (4) III-V cells because of their high performance and availability thanks to the multi-junction cell research for space applications over the last decade. Table 2 lists these four cells (InGaP, GaAs, InGaAsP and InGaAs) and their significant properties. The same table also shows the results of theoretical modeling studies for the selected group of sub-cells. Figure 6 shows the Spectral responses of these sub-cells superposed on the AM1.5 solar spectrum.

Table 2.
Selected III-V Sub-cells and Associated Energy Bandgaps

Sub-cell material	**InGaP**	**GaAs**	**InGaAsP**	**InGaAs**
Bandgap (eV)	**1.86**	**1.424**	**1.10**	**0.74**

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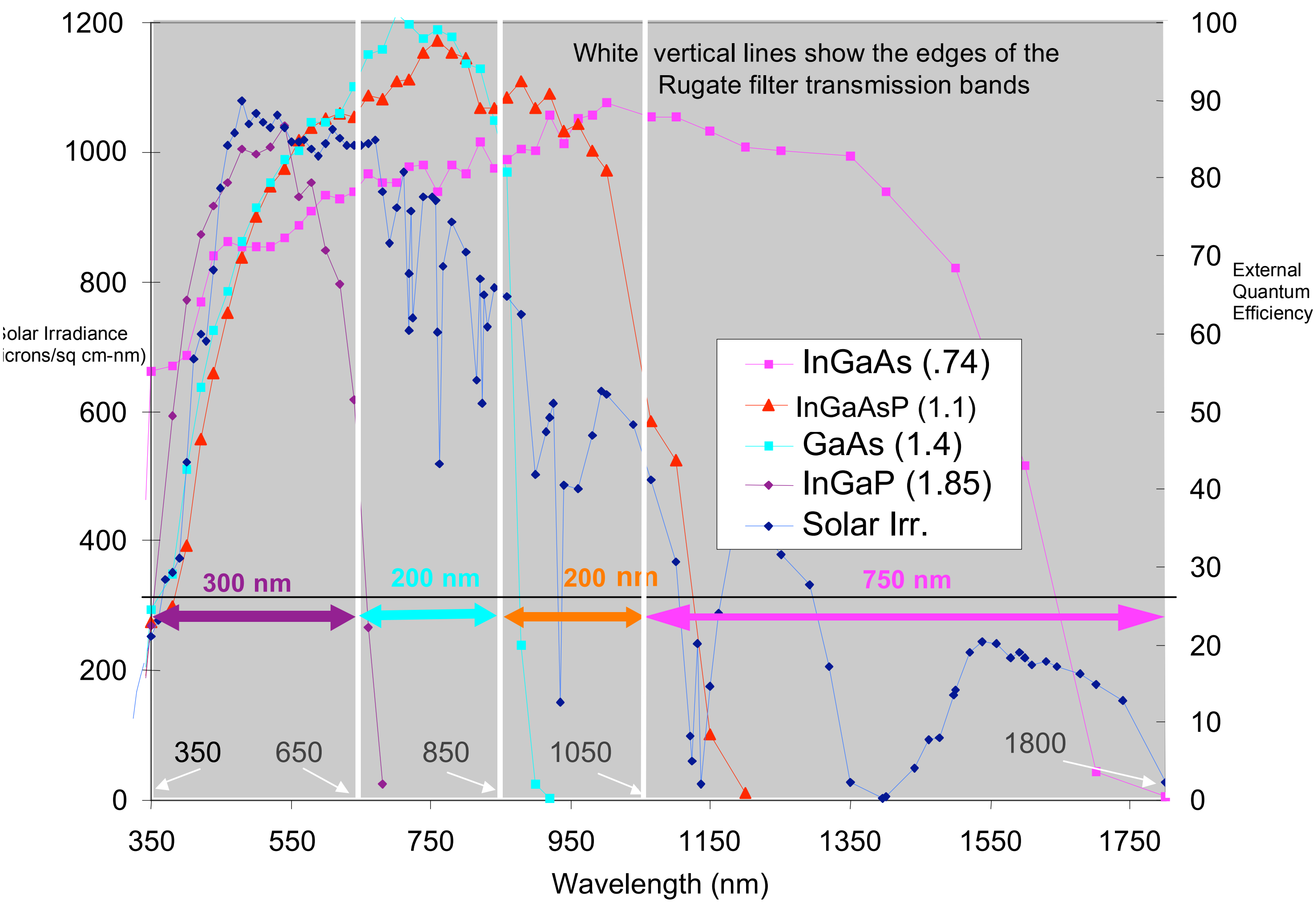


FIGURE 6. AM1.5 SOLAR SPECTRUM AND THE EXTERNAL QUANTUM EFFICIENCIES OF THE SELECTED III-V SUB-CELLS

Sub-task 2b

Narrow-band Rugate filters have been designed and manufactured successfully in the past by others. The challenge for this project was to model-broad band Rugate filters with no higher harmonics and side-lobs without sacrificing high reflection and transmission properties of the filters.

Four different Rugate filters were modeled for the selected sub-cells. Table 3 shows the respective transmission and reflection bandwidth ranges for these filters.

Table 3.
Rugate Filter Performances for the Various Transmission and Reflection Intervals

Sub-cell	Transmission Frequency Band (nm)/Average Transmittance (%)	Reflection Frequency Band(s) (nm)/Average Reflectance (%)
InGaP	**350-650 / 95.0**	**650-1800 / 99.7**
GaAs	**650-850/98.3**	**350-650/ 99.3 850/1800/ 99.0**
InGaAsP	**850-1050/ 98.0**	**350-850 / 99.5 1050/1800/99.5**
InGaAs	**1050-1800 / 98.2**	**350-1050 / 98.4**

Figure 7 shows the performance characteristics of a conjugate Rugate filter for GaAs as an example.

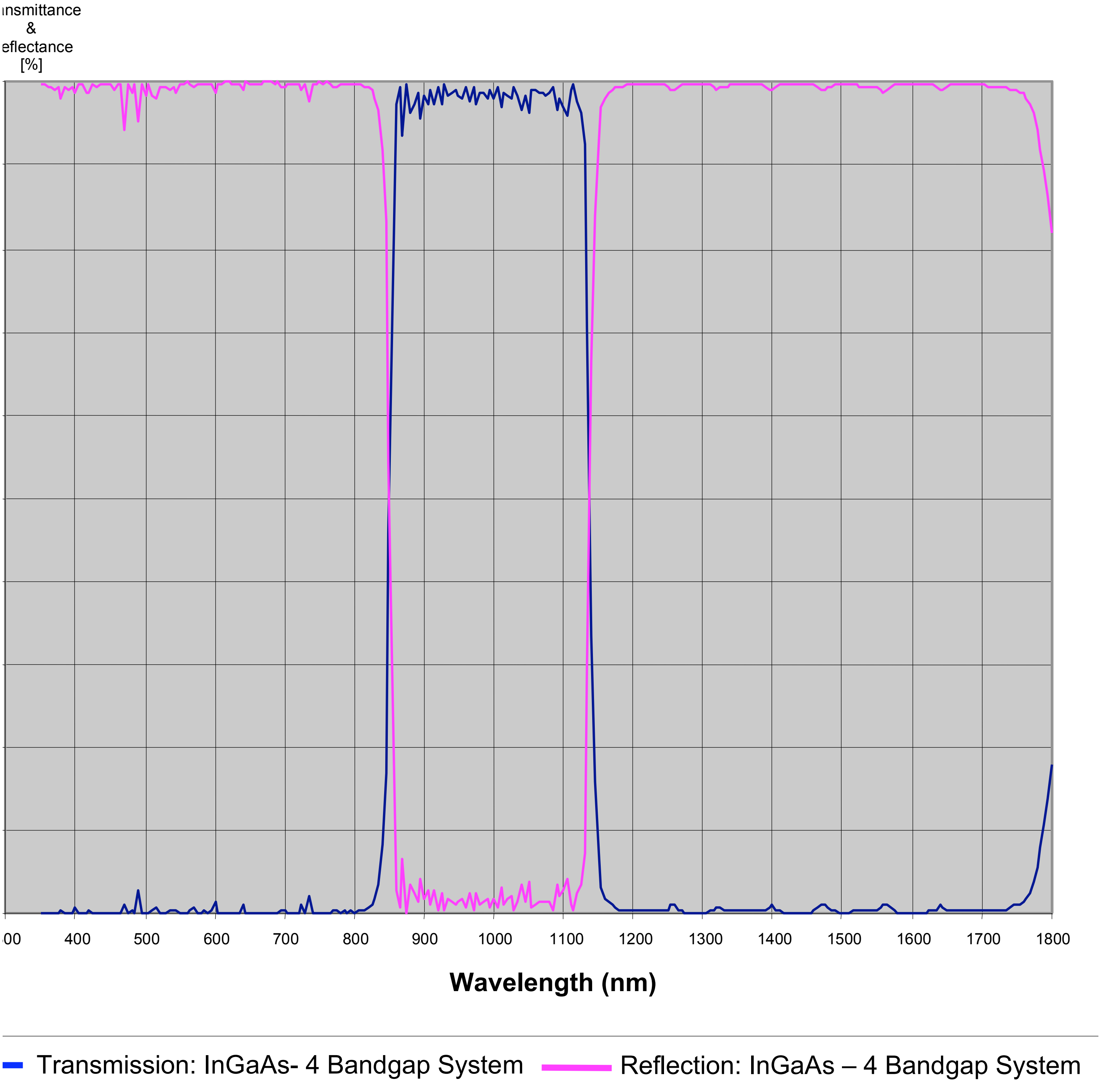


FIGURE 7. CONJUGATE RUGATE FILTER for InGaAs Sub-cell (Example)

Sub-task 2c

First, a proprietary cell modeling software by EMCORE was used to calculate the theoretical efficiency of the selected III-V sub-cells under various concentrations up to 100 suns. These computations assumed no grid shadowing and zero series resistance loss (Rs = 0). Then this model was coupled to a grid design software that is used to determine the optimum grid dimensions for the cells to minimize the shadowing and series resistance losses. The novelty of this approach is the introduction of the Photon Utilization Factor (PUF) that is unique to PVCC. The photons reflected by the highly reflective (99%) grid, the busbar and the active area of a given type of sub-cell are trapped in the cavity and have a certain probability (PUF) to return back and enter a same type of sub-cell. At this stage of the study a target PUF of 0.9 and a nominal concentration of 100 suns were assumed and the grid dimensions were optimized to maximize the collective cell efficiency for the selected set of III-V sub-cells. The results are shown in Table 4. (Note; The results for PUF = 0.8 and Concentration Ratio CR = 50 suns that were obtained by extrapolation are given under Sub-task 3c).

Table 4.

Optimized 4-Bandgap System Performance @ 100 suns

Sub-cell Material	**InGaP**	**GaAs**	**InGaAsP**	**InGaAs**	**Total**
Bandgap (eV)	**1.86**	**1.424**	**1.10**	**0.74**	**-**
Wgrid (μm)	**10**	**10**	**10**	**10**	**-**
Wbus (μm)	**350**	**350**	**420**	**520**	**-**
Grid spacing (μm)	**74**	**69**	**62.5**	**51.8**	**-**
Metal coverage (%)	**17**	**18**	**20.2**	**24.5**	**-**
Rtotal (Ω-cm2)	**0.022**	**0.021**	**0.018**	**0.014**	**-**
Jsc (mA/cm2)	**1089**	**1076**	**1043**	**1150**	**-**
Theoretical Jsc (mA/cm2)	**1110**	**1100**	**1070**	**1190**	**-**
FF	**90.2**	**87.4**	**83.9**	**77.3**	**-**
Theoretical FF	**91.7**	**89.3**	**86.3**	**80.5**	**-**
Theoretical Eff. (%)	**20.46**	**14.20**	**9.50**	**6.11**	**50.27**
Efficiency	**19.85**	**13.65**	**9.07**	**5.70**	**48.27**

Figure 8 shows the dependence of the collective cell efficiency on the concentration ratio CR and the series resistance R_S. The highlighted point on Figure 7 shows the collective efficiency at 100 suns for a cavity where the metallization of the cells is optimized.

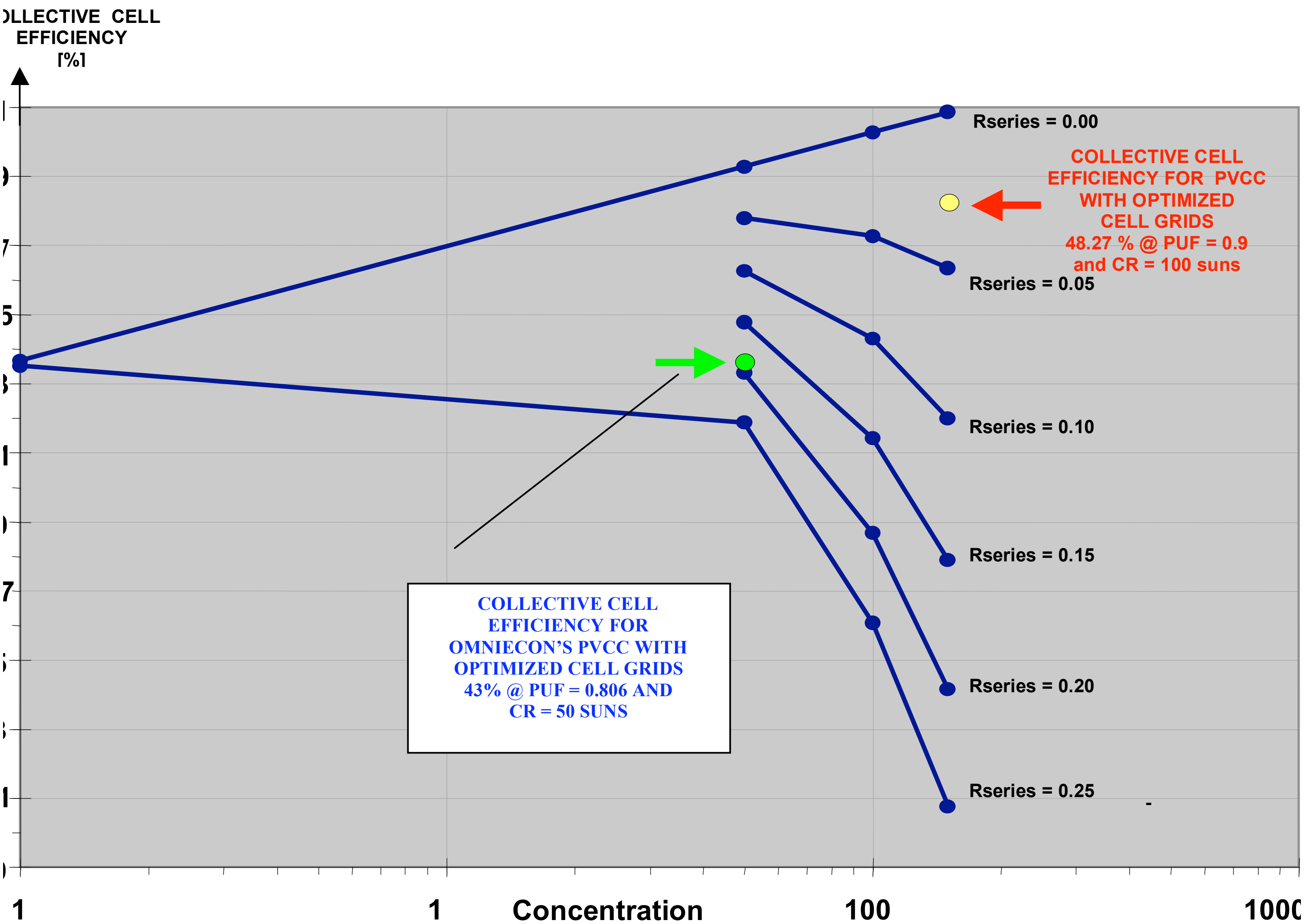


FIGURE 8. RESULTS OF EFFICIENCY MODELING FOR A 4-BANDGAP SYTEM AND DEGRADING EFFECT SERIES RESITANCE AT 100 SUNS AND ABOVE

Sub-Task 3a

OMNIECON's multi-facetted insect eye serves two functions: a) Formation of a composite aperture with a wider field of view (compared to a single facet) by overlapping the individual acceptance angles of the facets; b) Improving the ability of OMNIECON to collect more diffuse radiation from a larger portion (larger solid angle) of the sky. Both functions serve to optimize the amount of solar radiation through out the day and through out the seasons with no- or minimum tracking.

The optical modeling of the facets started with a Compound Parabolic Concentrator (CPC) shape for the facets. However, it was quickly realized that for a 7 facet system they would have intersection problems with each other when fitted on the same cavity. Figure 9 shows the Bezier optimized facets (replacing CPC) which evolved from our optimization studies. Bezier optimized facets allow a more close packed array when mounted on the cavity. Figure 10 shows the through put efficiency of a single facet as a function of the sun angle (0 sun angle means incident light is in the direction of the optical axis).

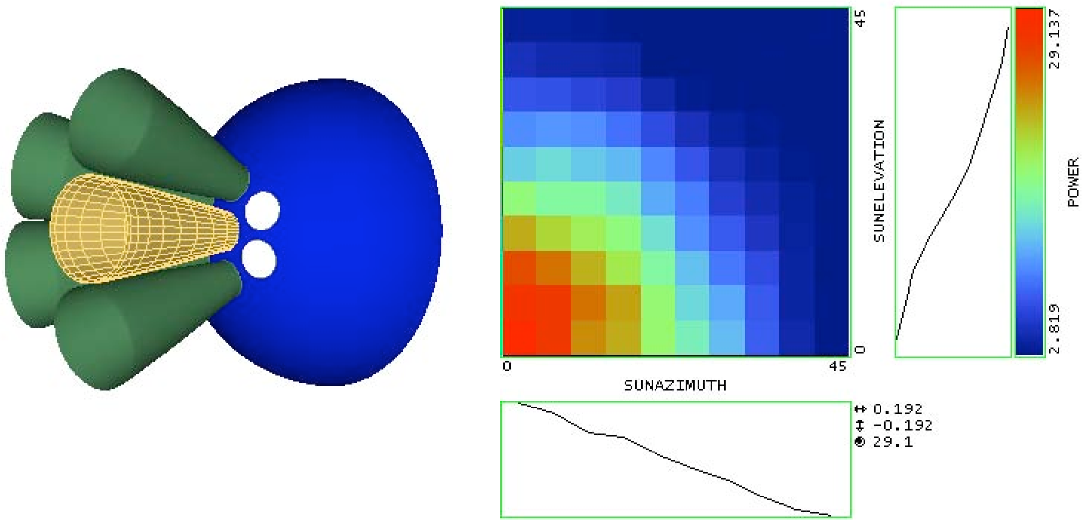


FIGURE 9. BEZIER OPTIMIZED 7-FACET ARRAY ATTACHED TO THE CAVITY

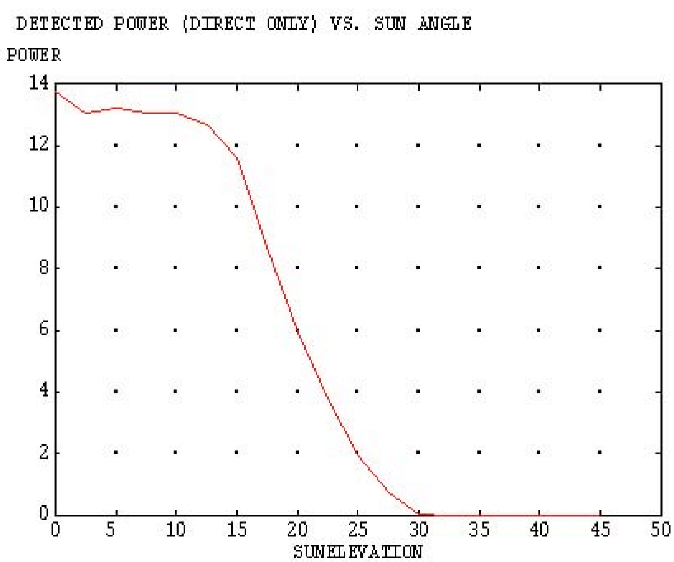
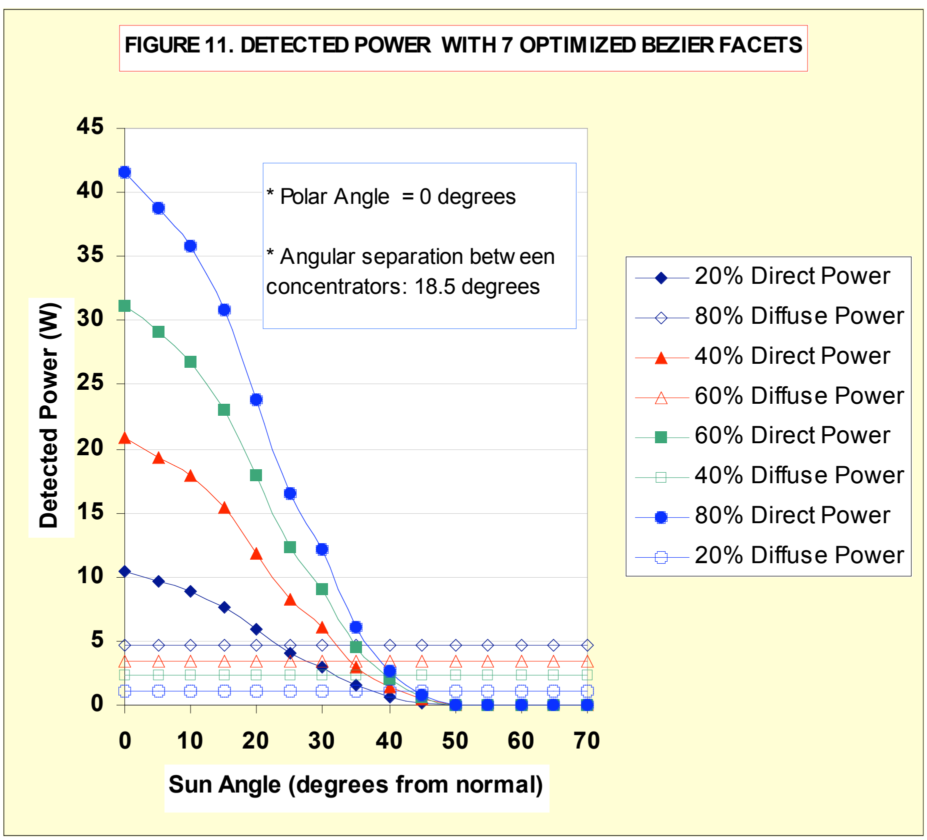


FIGURE 10. THROUGH-PUT EFFICIENCY OF A SINGLE FACET AS A FUNCTION OF THE SUN ANGLE (ELEVATION)

Sub-task 3b

Composite view angle of the insect eye optics consisting of 7 Bezier optimized facets was calculated by moving the suns position relative to the optical axis of the insect eye that coincides with the optical axis of the central facet surrounded symmetrically by six other facets. Although the aperture formed by the seven facets does not have a true circular symmetry the close–packed hexagonal shape of it can be considered a close approximation. Thus the performance of the insect eye as a function of the sun angle will be considered to be the same for the polar angle. For purposes of this discussion the sun angle represents the diurnal (east-west) movement of the sun) and the polar angle represents the seasonal (north-south) movement of the sun. The ASAP ray tracing program used for simulating the yearly performance of the OMNIECON provided also the option to vary the relative intensity of the direct and diffuse components of the solar radiation. Figure 11 shows the detected power inside the cavity as a function of the sun angle for a fixed (0 degree) polar angle and a 80% - 20% mix for the direct and diffuse components, respectively.



As it can be seen from Figure 10 the useful portion of the available field-of view is about +/- 30 degrees off-normal for the direct solar radiation. The diffuse component is independent of the angle as expected. The relative contribution by the diffuse radiation to the total power change depending on the relative intensities of the direct and diffuse components and of the solar angle. Table 5 lists the detected power by OMNICON as a function of various direct and diffuse solar flux levels. It interesting to note, that for the 20% direct- and 80% diffuse mix, the contribution of the diffuse component to total power detected is 31% and 61% at solar angles 0^0 and 25^0, respectively. This shows the importance of the insect eye optics in moderate climates.

Table 5.

Detected Power by OMNIECON as a Function of solar Angle for Various Direct and Diffuse Solar Flux Contributions

POLAR ANGLE	SUN ANGLE	20% Direct Power	80% Diffuse Power	40% Direct Power	60% Diffuse Power	60% Direct Power	40% Diffuse Power	80% Direct Power	20% Diffuse Power
0	0	10.404	4.662	20.808	3.496	31.211	2.331	41.615	1.165
0	5	9.689	4.662	19.377	3.496	29.066	2.331	38.754	1.165
0	10	8.947	4.662	17.894	3.496	26.841	2.331	35.788	1.165
0	15	7.702	4.662	15.403	3.496	23.105	2.331	30.807	1.165
0	20	5.947	4.662	11.894	3.496	17.841	2.331	23.789	1.165
0	25	4.119	4.662	8.238	3.496	12.357	2.331	16.477	1.165
0	30	3.032	4.662	6.063	3.496	9.095	2.331	12.126	1.165
0	35	1.514	4.662	3.027	3.496	4.541	2.331	6.055	1.165
0	40	0.679	4.662	1.358	3.496	2.037	2.331	2.715	1.165
0	45	0.208	4.662	0.415	3.496	0.623	2.331	0.831	1.165
0	50	0	4.662	0	3.496	0	2.331	0	1.165
0	55	0	4.662	0	3.496	0	2.331	0	1.165
0	60	0	4.662	0	3.496	0	2.331	0	1.165
0	65	0	4.662	0	3.496	0	2.331	0	1.165
0	70	0	4.662	0	3.496	0	2.331	0	1.165

Sub-tasks 4 and 6

Table 6 summarizes the critical input parameters and the performance results for OMNICON equipped with an array of seven Bezier optimized facets. The incident solar flux is coincident with the optical axis of the OMNIECON and consists of a 80% direct component and a 20% diffuse component. Table 5 below is used both for calculating the flux concentration inside the cavity (**Sub-task 4**) and the overall conversion efficiency of the OMNICON (**Sub-task 6**).

Table 6. Performance Summary for OMNIECON

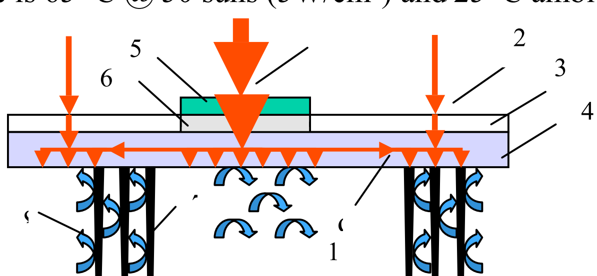
```
'INSECT EYE' CONCENTRATOR PARAMETERS - MULTIPLE QUATRATIC BEZIER CONCENTRATORS
SEMI-DIAMETER OF ENTRANCE APERTURE    =          0.0707 m
SEMI-DIAMETER OF EXIT APERTURE        =          0.0250 m
LENGTH OF CONCENTRATOR                =          0.25   m
CONCENTRATION RATIO                   =          8.00
AMGLE BETWEEN CENTERS                 =         18.500  DEGREES
EDGE THICKNESS                        =          0.0005 m
TOTAL COLLECTION APERTURE             =          0.110  m^2

SPVCC SPHERE PARAMETERS
AREA OF INTEGRATING SPHERE            =           0.503 m^2
LAMBERTIAN REFLECTANCE                =           0.991
SCATTER LEVELS                        = 151
SCATTERED RAYS  = 1        RAYS PER INCIDENT RAY

SOLAR INPUT
SUN ELEVATION ANGLE                   =                  0.0 DEGREES
SUN AZIMUTH ANGLE                     =                  0.0 DEGREES

SOLAR INCIDENT IRRADIANCE                    =          800.00 W/m^2
SKY INCIDENT IRRADIANCE                      =          199.90 W/m^2
COLLECTED POWER (AT CONCENTRATOR ENTRANCE)   =          106.97 W
COLLECTED POWER (AT CONCENTRATOR EXIT)       =           54.77 W
ZONE 1 STATISTICS
  IN-BAND SPHERE MULTIPLIER         =          4.005
  MERIT FACTOR                      =          0.88
  POWER (IN BAND) ENTERING CAVITY   =         20.1 W
  POWER INCIDENT ON DETECTOR(S)     =         16.3 W
  POWER DETECTED                    =         16.3 W (CPUF =     0.812)
ZONE 2 STATISTICS
  IN-BAND SPHERE MULTIPLIER         =          5.078
  MERIT FACTOR                      =          1.11
  POWER (IN BAND) ENTERING CAVITY   =         12.5 W
  POWER INCIDENT ON DETECTOR(S)     =          9.7 W
  POWER DETECTED                    =          9.7 W (CPUF =     0.774)
ZONE 3 STATISTICS
  IN-BAND SPHERE MULTIPLIER         =          5.078
  MERIT FACTOR                      =          1.11
  POWER (IN BAND) ENTERING CAVITY   =         10.0 W
  POWER INCIDENT ON DETECTOR(S)     =          8.1 W
  POWER DETECTED                    =          8.1 W (CPUF =     0.813)
ZONE 4 STATISTICS
  IN-BAND SPHERE MULTIPLIER         =          4.662
  MERIT FACTOR                      =          1.02
  POWER (IN BAND) ENTERING CAVITY   =         12.2 W
  POWER INCIDENT ON DETECTOR(S)     =         10.1 W
  POWER DETECTED                    =         10.1 W (CPUF =     0.824)
-----------------------------------------------------------------------
TOTAL POWER DETECTED (ALL ZONES)    =         44.1 W (CPUF =     0.806)
TOTAL POWER EXITING CAVITY          =          6.1 W
TOTAL POWER ABSORBED BY CAVITY      =          4.5 W
```

It is important to note that the physical size restraint in attaching a multitude of facets (seven of them) to the same cavity forced us to increase the radius of the cavity by a factor of about 10. This results in an automatic area increase of 100 fold inside the cavity. Consequently the resulting concentration should be at least 100 times less than the expected 50 suns concentration for the same aperture area of the insect eye. The actual dilution of the concentration is even less, that is because the overall aperture area of the facets (1099.2cm^2) is 4.6 smaller than the cavity area (5030cm^2). Thus a flux dilution of 460 is expected as compared to 50 suns concentration i.e.

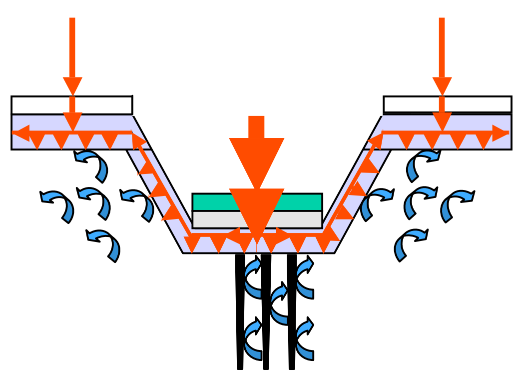
0.11suns. This is in agreement with the ray tracing result: Total power 54.7W inside the cavity (detected + escaping + absorbed components inside the cavity) divided by the cavity area (5030cm2) i.e. 0.1 suns. Although this concentration is totally unacceptable the overall photon detection efficiency (not conversion efficiency) of OMNIECON is high. The detection efficiency is calculated by dividing the total power detected (44.1W) by the collected power at concentrator entrance (106.97W) or 41.23%. This result is based on 80% direct and 20% diffuse radiation. If standard methods to calculate concentrator efficiencies is used the detected power is divided by the direct component of the solar flux. In this case OMNICON's detection efficiency becomes 51.53 %. The overall conversion efficiency can than be calculated by multiplying the detection efficiency with the collective cell conversion efficiency calculated under Sub-task 2 i.e. 43.22 %. Thus OMNICON's overall conversion efficiency becomes 22.27% if standard methods are used to calculate the concentrator efficiency.

Sub-task 5

Although active air- or liquid cooling systems where the working fluid is pressurized to increase the flow rate and the heat transfer are more powerful to remove waste heat from the cells they are expensive and require more maintenance. They also lower the system reliability because of the wear and tear of the moving parts. Therefore they should be avoided by passive cooling methods whenever it is possible. For this project we considered free air convection cooling using the ambient air. The heat generated in the cell is spread by conduction over the total body of the OMNIECON structure. Figure 12 shows the thermal path (heat flow from cell to ambient air) for the two configurations considered in this project The results obtained for both configurations were similar. In reality the facetted optics attached to the sphere is also highly effective in increasing the convective heat transfer as the facets themselves act like fins if they are made of metal. They were omitted in our calculations to have a conservative estimate of the cell operational temperature. The analytical thermal model assumes a cavity with aluminum walls. External cooling fins are attached to the sphere to increase the convective surface area. The bottom of each cell as well as the ceramic substrate surfaces are metallized for soldering purposes. The ceramic substrate (Aluminum Nitride) underneath the cell serves as an electrical insulator with a relatively high thermal conductivity (175 W/m ^{0}K). The calculated operational cell temperature is 65^0 C @ 50 suns (5W/cm^2) and 25^0 C ambient Temperature



CONFIGURATION NO. 1



CONFIGURATION NO. 2

– Heat input into solar cell
– Heat input into diffuse reflector
– Diffuse reflector
- Cavity wall (aluminum)
– Solar cell
- Cell substrate
- Heat exchanger fins (aluminum)
- Convection cooling by air
– Thermal path for waste heat removal

FIGURE 12. THERMAL MODELS FOR WASTE HEAT REMOVAL BY FREE CONVECTION

Sub-task 7
This task involves the development of a preliminary OMNIECON module design and explore cost effective manufacturing processes for the three key components i.e. The cavity, facetted insect eye and certain aspects of the sub-cells. Our findings are outlined under Project Outcome, Subtask 7.

Project Outcomes
The outcome of our analytical studies for the Sub-tasks 1 through 7 were:

Sub-task 1
The OMNIECON design including insect eye optics resulted in a larger than expected cavity with a diameter of 40 cm. Four different III-V sub-cell types inside the cavity, coated with conjugate Rugate filters occupied 75% of the available wall area (5,030 cm^2). This cavity when attached to the insect eye optics consisting of 7 facets achieved an average PUF of 0.806.

Discussion:
Although we did not achieve our goal of PUF = 0.9, our result, i.e. PUF = 0.806 is quite encouraging. The difference in the PUF is due to the increased escape probability for the photons from the cavity caused by the increased number of entrance apertures from 1 to 7. (PUF was originally estimated for a single entrance aperture).

Sub-task 2
a) With the cooperation of space cell manufacturers (EMCORE, Spectrolab) and JPL, UI^2 has identified four (4) III-V sub-cell candidates that cover the solar spectrum congruently and fully. The set includes GaInP, GaAs, InGaAsP and InGaAs.

b) In cooperation with Barr associates UI^2 has developed four different Conjugate Rugate filter models for the selected four sub-cell candidates. Each Rugate filter passed the 98% to 99% criteria in terms of their transmission and reflection characteristics.

c) A four band-gap, III-V system consisting of the selected sub-cells (Subtask 2a) and covered with conjugate Rugate filters (Sub-task 2b) reaches a collective cell efficiency of 43% at a concentration of 50 suns and PUF = 0.806 (Sub-task 1).

Discussion:

a) Thanks to the extensive multi-junction cell studies over the last decade, excellent III-V sub-cells that respond to various frequency bands of the solar spectrum are available. The spectral response functions of the selected sub-cell group consisting of GaInP, GaAs, InGaAsP and InGaAs cover the solar spectrum congruently and fully.

b) It was proven that broad-band “pass-or-reflect” Rugate filters can be designed successfully (this does not guarantee their manufacturability). The high reflectance and transmittance values (~99%) and the respective flat responses of the modeled Rugate filters are most encouraging.

c) Although our predicted collective efficiency is below our target of 45%, it is still 21% higher than the world record reported by Spectrolab in 2001 obtained with multijunction cells [2]. At a PUF of 0.9 (as achievable with single-aperture cavities) the collective cell efficiency becomes 48.27 %.

Sub-task 3

a) A compound insect eye optics system consisting of seven facets can collects solar radiation from –30 degrees to +30 degrees off the normal corresponding to a solid angle of 0.25 π steradiance or 25 % of the hemisphere. The normalized intensity of the detected power as a function of sun-angle from Zenith changes similar to a bell curve with a peak at normal incidence and dropping to about 30% of the peak at +/-30 degrees, respectively.

b) The light through-put efficiency of a single the facet at normal incidence is 87.2%. The overall through-put of the facetted insect eye consisting of 7 facets at normal incidence is 63 %.

Discussion:

a)Although the insect eye aperture does not have perfect circular symmetry it closely approximates it. Thus solar- and polar angles are interchangeable. In simple terms this means that the field of view for diurnal and seasonal movement of the sun are both 60 degrees. If the sun is assumed to be a point source this implies that the OMNIECON must be tilted back and forth twice every 24 hours in the East-West direction to be able to collect solar radiation during the +/- 4 hours from noon. To follow the seasonal movement of the sun OMNIECON must be tilted twice per year in the North-South direction. Thus the tracking movement cannot be eliminated fully, but a very simple device or manual adjustment can be utilized.

b) The light trough-put efficiency (87.2%) for a single facet at 100% direct, normal incidence is as high as expected. The overall through-put efficiency of the facetted insect eye consisting of 7 facets at normal incidence (63 %) is below the expected 80%. This is due to the dome shaped aperture of the insect eye and the particular angular response of the Bezier optimized facets. The overall light through-put efficiency can be further optimized by using higher order Bezier surfaces.

Sub-task 4

Calculated Flux density inside the cavity is 0.11 suns.

Discussion:

This very low concentration is about 455 times smaller then the expected concentration of 50 suns. There are two geometrical reasons for this lack of flux density. a) To accommodate 7 facets without any physical intersection problems it is required to increase the sphere radius from about 2 cm to 20 cm. This leads to a surface area increase (inside the sphere) by a factor of 100. b) The entrance aperture area for the solar radiation extended by the 7 facets is 4.57 times smaller then the interior cavity area. Given the geometrical requirements a loss in concentration (W/cm^2) by a factor of 457 is expected. This is in agreement with our ray tracing studies.

Sub-task 5

The facets and the sphere are assumed to be made of aluminum and the cells are thermally coupled to the sphere via high conductivity ceramic. The heat generated in the cells is distributed across the module via conduction and is dissipated from the surface module via free air convection. At an ambient temperature of 25^0 C the steady-state cell temperature inside the PVCC operating at 50 suns is calculated to be 65^0 C.

Discussion:

This result (65 degrees C cell operational temperature) is very satisfactory for a concentrator operating at 50 suns. This temperature is slightly higher than a conventional flat plate PV panel operating under 1 sun or no concentration. Thus the expected performance degradation due to concentration caused temperature increase is modest. For a nominal cell temperature coefficient of -0.06 [%/ ^{0}C] the expected efficiency drop due to temperature increase is 2.4 % (absolute) as compared to the performance of the same cell at 25^0 C.

Sub-task 6

The calculated overall efficiency of the fully assembled OMNIECON was found to be 22.27 % at 25^0 C and 19.87 % at 60^0 C (average operational temperature). These efficiencies were calculated by using concentrator standards i.e. the power output was divided by the direct component of the solar flux.

Although these efficiencies are below our target of 38% they are still higher than any other terrestrial concentrator module efficiencies reported in the literature.

Sub-task 7

The facetted insect eye optics, the internally illuminated cavity, and the broadband Rugate filters deposited on cells are completely new ideas in the field of solar energy and no manufacturing experience in these areas exist.

Therefore UI^2 investigated a multitude of fabrication processes developed in other technology sectors. After extensive studies we have come to the conclusion that the following three technologies are best suited for the facet-optics, the cavity and the Rugate filter coatings on the cells:

a) The complete assembly of facets can be manufactured by nickel electroforming in a one step process by using highly polished steel molds;

b) Cavities can be electro-formed by spin-forming of aluminum very cheaply and quickly;

c) Broadband Rugate filters can be deposited relatively faster by utilizing Plasma Enhanced Chemical vapor deposition.

Discussion:

Known Solar/PV manufacturing methods are not suitable for the proposed OMNIECON design. The multi-directional insect eye optics and the PVCC configuration require new manufacturing processes that must be developed or adapted from other technology areas. Further studies in these areas are necessary.

Conclusions

For the sake of brevity we list our conclusions for different subtasks in Table 7 below:
Note: The risk factors quoted below are based on a 0 to 100 scale. Increasing numbers mean increased risk of the associated R&D.

Table 7.
Overview of Project Outcomes and Risk Assessment

Sub-task No.	Measurable Parameter	Technical Objective	Results of Technical Analysis	Risk Factor (RF) and Conclusions (C)
1	Photon Utilization Factor	0.90	0.806	RF: <5 C: Successful, can be improved
2a	Selection of Candidate III-V Sub-cells	Complete Coverage of Solar Spectrum	Complete Coverage of Solar Spectrum	RF: 0 C: Highly Successful
2b	Broadband Transmission and Reflection Characteristics of Rugate Filters	Trans. ~ 99% Refl.~99%	Trans. ~ 99% Refl.~99%	RF: 0 C: Highly Successful
2c	Collective Cell Efficiency	45%	43%	RF: <5 C: Successful, can be improved
3a	Useful Field of View Angle	-30^0 to $+30^0$	-30^0 to $+30^0$	RF: 0 C: Successful, 2 adjustments per year and per day
3b	Optical Through-put of the Insect Eye at normal incidence	Single Facet: 90% Complete Eye:80%	Single Facet: 87.2% Complete Eye: 63%	RF(Single Facet): 0 C(Single Facet): Successful RF(Complete Eye): 80 , C(Complete Eye): R&D is necessary
4	Flux Density inside the Cavity	30 to 50 suns	0.11 suns	RF: 90 C: Not successful, High risk R&D necessary
5	Operational Cell Temperature	55^0 C to 65^0 C @ T_a= 25^0 C	65^0 C @ T_a= 25^0 C	RF: 0 C: Successful
6	Collective Module Efficiency	> 38 % @25^0C	22.27% @ 25^0C 19.87 %@ 65^0 C	RF: 50 C: Good Performance, needs R&D
7	Manufacturing	Cost effective Manufacturing Processes	Cavity: Spin Forming, Facet Optics: Electro-Forming,	RF: 80 C: No existing experience in Solar field, Needs R&D

Recommendations

With the exception of Sub-task 4 (concentration ratio) the project can be considered successful to very successful. First and foremost the PVCC unit which converts the concentrated solar energy into electricity works extremely well. At high concentrations world record performances are expected. This is a very positive outcome of this project and UI^2 is looking forward to further develop this unique design with a different concentrator (see below). Unfortunately the extremely low concentrations caused by the geometrical (structural) constraints in mounting the multi-faceted insect eye on the cavity represent a major problem (Sub-task 4). High concentration is a major requirement for this particular project to be successful as it reduces the effective cost directly and proportionally. Thus without the benefit of high concentration no savings in cell costs can be realized and therefore the electricity cost cannot be reduced. This remains true in spite of the extremely high conversion efficiency of the PVCC and omni-directional power collection capability of the multi-facetted insect eye. In UI^2's opinion the extensive R&D which is required to resolve the problems (involving Facetted Insect Eye Optics), represent too high a risk and should not be pursued. Instead we strongly recommend that the highly valuable PVCC knowledge, we already have is used in conjunction with a different concentrator type for the full system to reach its maximum potential. This recommendation is in full agreement with our wish to make the best use of the already incurred investments and efforts by the Energy Commission and UI^2.

In our studies with the PVCC we discovered that a very high efficiency and very high concentration Dish/PVCC system can be built when PVCC is optically coupled to a very large parabolic dish concentrator via a secondary stage concentrator. The parabolic dish combined with the secondary stage can generate very high concentrations (20,000 suns) at the entrance to the cavity. Analytically we have shown that flux densities in the order of 500 suns inside the cavity are possible with such a Dish/PVCC system. At this level of concentration the "effective cell cost" drops dramatically (i.e. 500 times) and the cost of solar electricity becomes highly competitive (~$3/W) in agreement with the fundamental goal of this project. Appendix I of this Final Report describes the proposed Dish/PVCC system in more detail.

UI^2 is fully prepared to move up into the Stage 3 Phase (i.e. Research and Bench Scale Testing Phase) with the Dish/PVCC concept if Gate 2 (i.e. Research approval) decisions by the Energy Commission are in favor of the proposed change in the concentrator design.

Public Benefit to California

Since June 2000 (when UI^2 has submitted this proposal) California has experienced the most volatile electricity market in the history of the State. Gross purchase prices of a kilowatt hour of electricity have first climbed from a few pennies to as much as $1.50/k Whr and then forced down to below $0.10/kWhr by the intervention of the state by means of long term power purchase contracts. Associated with this emergency solutions are hidden costs for tax payers in the order of billions of dollars that will have to be faced in the future. The present energy situation in California is not satisfactory nor stable. Compared with the national average price paid by all the consumers in the US, Californians pay more than twice the amount per kilowatt hour. Even this cost is predicted to rise in the future for the following reason: Given the environmental and cost disadvantages of coal and nuclear power in California, the state will depend mostly on gas fired power plants and imported power from its neighboring states. This scenario inevitably calls for speculative electricity cost escalation as demand increases. However, California harbors enormous solar resources that can be directly converted into

electricity using photovoltaic (PV) technology. Within foreseeable time PV can contribute more than 20 percent to the energy mix in California. Public opinion supports a move in this direction as manifested recently by the SMUD's solar program overflowing with takers and the voters in San Francisco overwhelmingly approving a $100 million revenue bond for solar and wind energy projects.
Undeniably California will greatly benefit from the full scale commercialization of PV There are however several obstacles that block the industries entry into the existing vast market. These are:
a) High cost of efficient PV equipment (mostly flat plate PV modules) stemming from high manufacturing cost of the cells (inexpensive but low efficiency cells increase the Balance of System (BOS) cost and require larger real estate);

b) Existing very limited production capacity for high efficiency cells to supply a large market and also the large investments required to build up the necessary manufacturing capacity that can provide the a large market;

c) Severe and unavoidable raw material shortages for high efficiency cells in the event a Giga-watt market emerges.

High Concentration PV technology mitigates or circumvents these three problems as follows:
A concentrating PV device intercepts the solar radiation by means of a large area lens or by a curved mirror and focuses it onto a much smaller PV target that converts it into electricity. This avoids the necessity to cover the whole intercept aperture with expensive solar cells yet the system generates about the same amount of power that a flat plate panel with the same aperture would generate. (Actually high efficiency PV concentrators in general produce more electricity for the same intercept area, because of the increased cell efficiency as a result of concentration. In the case of PVCC this increase could be 200% to 300%). The reduction in the amount of cells in a concentrator device is inversely proportional to the concentration ratio of the device. At high enough concentrations (e.g. 500 suns) the "500 times less cells are effective" cell cost [$/W] is reduced by about 500 times because the required cell area is 500 times less.
We have the analytical proof that the proposed high concentration Dish/PVCC will bring down the cost of solar electricity to $1-3/Watt. This concentrator technology is highly suitable for California and particularly for the southwest regions of California where the direct component of the solar radiation is abundant.

Development Stage Assessment
Important Note: In the section on "Conclusions" we have stated that as a result of difficulties experienced under Task 4, namely extremely low flux densities (not total power) in the cavity we do not recommend to continue the R&D work on the " Multi-facetted Insect Eye Optics". Instead we recommend that the highly successful PVCC concept should be utilized in conjunction with a Dish/PVCC system that circumvents the problems mentioned and represents a very promising potential product for large scale power production. Unlike OMNIECON, a Dish/PVCC concentrator is a tracking device that generates 30 to 35 kW power.at an efficiency of 38% or better. Our Development Stage Assessment presented here is based on the Dish/PVCC system that is based on the spectral splitting process in a light confining cavity as is the case with OMNIECON.

Marketing

Most of the information given in this section is based on studies conducted in conjunction with the Concentrating Solar Power Industry Group of which UI^2 is an active member.

In view of the High Concentration Photovoltaics (HCPV), initial markets for HCPV power are in seven states that comprise the Southwest region of the United States (plus one or two adjoining States). The target states are Arizona, California, Colorado, New Mexico, Nevada Texas and Utah. Candidate buying entities within these states include local utilities, power producers (or distributors) needing to meet the portfolio standards, Federal installations, and State county and local governments. Many of the States of the Southwest enacted electric power laws that promote, or actually provide minimum markets for renewable energy and in a few cases specifically for solar energy. The total electric power need of all of the western states is about 1,100 billion kWhr. Only 3% of the land that has premium solar resource (>7kWhr/m2/day) within the region of the 7 target states can produce that amount of electric power.

In spite of this enormous potential and the associated market for HCPV generated electricity, The State of California and Federal policies support solar energy only marginally. A major initiative is necessary to change the present scenario into one that strongly supports development of highly advanced, cost effective and reliable solar technologies like HCPV to build up public confidence and acceptance.

Present break-through technology now being developed under this EISG Program has the potential to bring about this positive change in public opinion.

Engineering / Technical

- Technical analysis of the Dish/PVCC concept has already been completed
- The Dish/PVCC concept involves a large parabolic dish coupled to a PVCC as described in the main body of this report. The unit operates @ 500 suns and generates about 35 kW electric power. Expected system conversion efficiency is over 38%.
- As the proposed system relies on photovoltaic conversion of solar energy, by definition these systems do not utilize any moving parts for the conversion process (unlike theStirling Engine for example) and operate at temperatures close to ambient. Thus the reliability and maintainability are much higher than high temperature solar thermal engines (like Stirling, Bryton, Power Tower, etc.). Tracking parabolic dish technology is a mature technology with high reliability and maintainability.
- Technical feasibility of the Dish/PVCC system requires only the feasibility demonstration of the PVCC unit and of the secondary concentrator that couples (optically) the dish to the PVCC. The Dish itself is a well established technology. In Stage 3 UI^2 is planning to build a 5kW prototype that can be tested with an existing solar test facility at the National Renewable Energy Laboratory (NREL) under the Department of Energy (DoE) in Golden, Colorado.
- The cost of developing the prototype and testing it at NREL will be about $950K.
- The regulatory compliance is secured by the fact that the testing and verification at NREL complies with the National Standards for testing concentrators which in turn complies with regulatory requirements in general.
- Major competitors in the HCPV arena are Amonix, CA and Concentrator Technologies, Inc., CA. Both companies do not present a real threat to our technology as their concentration power and conversion efficiencies are <300 suns and < 20%, respectively. Thus their potential to reduce the electricity cost is much less than UI^2's Dish/PVCC

concept. In terms of their developmental stage both companies are at Stages 4 and 5 and are more likely to get investors or future customers attention.

Legal / Contractual

- All proprietary information including technical drawings regarding the PVCC and Dish/PVCC systems has been documented in form of a patent disclosure and submitted to a patent lawyer. At the time of this writing the final draft of the respective patent application is being completed by the said lawyer.
- No permits are required for any component of the PVCC system itself and its use in conjunction with concentrator dishes.
- As a small high technology company UI^2 does not have the resources to complete the planned R&D efforts and the subsequent commercialization by itself.
- If R&D funds under the PIER program will be made available to UI^2 there will be a royalty potential for the PIER program as the patents will be fully owned by UI^2.
- The Dish/PVCC concept is being developed for the new US alternative power market. Building and operating such a power plant requires multiple participants including, equipment and plant providers, project developers, plant owners and operators and power purchasers. In this chain of roles UI^2 is concerned only in providing equipment.
- In order to manufacture and market the equipment UI^2 has identified and contacted several potential partners including SES/Boeing, SAIC and Duke Solar.

Environmental, Safety, Other Risk Assessments / Quality Plans

- HCPV plants are environmentally friendly and produce no emissions
- There are no perceived risks that might result from this concept.

Strategic

- The proposed Dish/PVCC concept fits with the PIER Program Area "Renewable Energy Technologies"
- Presently there are no links to other PIER projects

Production Readiness

- For commercializing the product UI^2 is planning to form a partnership with a larger company like SES/Boeing, SAIC or Duke Solar. These are well established companies with PV technology products beyond stage 7.
- The motivation for SES/Boeing and SAIC to consider partnership is the higher reliability and now the higher efficiency of the Dish/PVCC system as compared to their present Dish/Sterling product. Duke Solar is a multi-technology equipment and plant supplier that is constantly looking for the most advanced and cost efficient equipment. All these three companies have the financial stability and resources to produce the product.

Public Benefit / Cost

- Public Benefit/Cost ratio can be best calculated once the product is fully commercialized and the over all benefits as well as the total cost to the public are known. At this point the PIER Program has spent $ 74,992 over a period of 12 months and secured the successful completion of Stage 2 of a highly promising product. Although the future benefits cannot be expressed in terms of $'s yet it is appropriate to mention the benefits in global terms here:

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Development	5 Product Development	6 Demonstration	7 Market Transformation	8 Commer-cialization
Marketing								
Engineering/ Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production Readiness								
Public Benefits/								

- Energy Security: Domestically produced energy decreases reliance on fuel sources outside US borders and promotes energy independence, thus increasing energy security.
- Employment: A greater fraction of HCPV energy costs are manpower related than for fossil fuels; there are thus more jobs per kilowatt-hour of output than for fossil powered plants. (For example at $3/Watt a 1000MW plant will create 10,000 high value added jobs).
- Environment: HCPV plants are environmentally friendly and produce no emissions. Thus the "external costs" like health related costs to the public, associated with the fossil powered plants are avoided.
- Export: Successful penetration into U.S. markets translates into a strong export potential where competing energy costs are often higher.

Based on the foregoing, national and State benefits result if HCPV can be established as a viable contributor to national and State energy needs. Realization of the benefits hinges on the potential for the HCPV success in transiting the R&D and market entry stages to a sustaining commercial status.

Development Assessment Matrix

Appendix I

DISH/PHOTOVOLTAIC CAVITY CONVERTER (PVCC) SYSTEM FOR ULTIMATE SOLAR-TO-ELECTRICTY CONVERSION EFFICIENCY GENERAL CONCEPT AND FIRST PERFORMANCE PREDICTIONS

Dr. Ugur Ortabasi
United Innovations, Inc.

Background: Interest in **H**igh **C**oncentration **P**hoto**V**oltaics (HCPV) for terrestrial applications has grown significantly in recent years. The major force behind this quickly evolving HCPV technology is the availability of very high efficiency solar cells that operate reliably under high concentrations of 500 to 1000 suns and above. The strong impact of high concentration on the cost of electricity is not only the relative improvement in cell performance, but is also the dramatic reduction in the amount of cells that are needed to build a solar power plant of any required generation capacity. Above 500 suns concentration, even very expensive, high performance space cells become affordable for terrestrial use because the "effective" cell cost due to concentration is minimized. Higher cell performance is also a key determinant of the electricity cost since it strongly impacts balance of system (BOS) and real estate costs. On the PV cell supply side, high concentration has a "capacity multiplier" effect that can increase the present power generation capacity by more than 500 times. Thus, reliable HCPV technology that combines high conversion efficiency with high concentration can bring the electricity cost down and become a major energy source in the near future.

Objective: This brief note summarizes the results of United Innovations, Inc.'s (UI^2) extensive analytical studies involving a novel solar-to-electricity conversion system called the Photovoltaic Cavity Converter (PVCC). The overall objective of this R&D, supported by a team of experts from numerous technical disciplines, is to achieve an ultimate system conversion efficiency using UI^2's "spectral screening" approach in a cavity that allows maximum use of the available solar spectrum by a variety of cell types. The underlying concept shown in Figure 1A involves a Dish/PVCC system that consists of a primary parabolic concentrator, a secondary, non-imaging concentrator, and a spherical cavity (PVCC) that has a small port (aperture) for the highly focused solar flux (~ 20,000 suns) from the secondary concentrator to enter. The trapped photon energy inside PVCC is converted to electricity by four different type (different bandgap) single-junction III-V cell groups (e.g. InGaP, GaAs, InGaAsP, and InGaAs) that line a certain fraction of the interior PVCC surface. The rest of the PVCC interior not occupied by the cells is coated with a highly reflective lambertian material. The cells of the same type are inter-connected to form strings that are voltage matched among each other.
The spectral response functions of the selected cell types congruently cover the solar spectrum wavelengths from 350nm to 1800nm. Individual cells forming the strings are covered with high quality conjugate Rugate filters that have nearly perfect transmission and reflection characteristics. A conjugate Rugate filter transmits only the portion of the solar spectrum that matches the spectral response of the cell underneath it, and reflects the rest. The photons reflected by the non-matching cells or by the diffusely reflecting cavity wall enter a "recycling" process within the cavity. The small flux entrance port of the cavity allows only a small fraction of the photons to escape. Given the high average reflectance of the Rugate filters and that of the PVCC wall, a large fraction of the photons introduced into the cavity ultimately find and enter a matching cell with the proper spectral response. This spectral screening process of photons by the Rugate filters is equivalent to the "spectral splitting" method previously reported in the literature (JPL's Rainbow project). The major difference in UI^2's concept is the significantly increased photon economy due to the recycling process within the small confinement of the PVCC.

Results: Analytical studies and the optimization results achieved under this project involved: A) Computer Modeling of Dish/Secondary Concentrator Optics; B) Interior Optical Modeling of PVCC; C) Cell Modeling; D) Rugate filter Modeling; E) Thermal Modeling; F) Structural Analysis; and, G) Performance Predictions. Item G, Performance Predictions, incorporates and utilizes all of the results obtained under items A to F. In a parallel study to this project, UI^2 designed and optimized a 100X, 1.5 kW prototype. This prototype concept is based on a four bandgap system consisting of the III-V cells listed above. The UI^2 team's combined modeling studies with realistic system parameters predicted a "collective" PVCC efficiency of 47.07%. The predicted cell operational temperature, photon utilization factor, and photon escape probabilities were: 55C, 0.90 and 2.5%, respectively. As the next phase of this project, UI^2 is planning to design and build a 5kW PVCC prototype that operates at 500 suns. This unit will be tested either by using an existing dish or the HFSF facility at the National Renewable Energy Laboratory in Golden, Colorado.

Conclusions: Based on UI^2's analytical results, the PVCC concept may reach the highest conversion efficiency that is potentially possible with multi-bandgap cell systems. Many challenges including the limited material choices facing multijunction cells with vertical architecture are avoided by the laterally configured, independent single junction cell strings. In the case of UI^2's Dish/PVCC system, the projected "collective" cell and system level efficiencies for a four bandgap concentrator system at 500X are over 50% and 38%, respectively. At this unprecedented system efficiency, HCPV technology based on UI^2's PVCC conversion method will be capable of making a major breakthrough in the production of low cost electricity from sunlight.

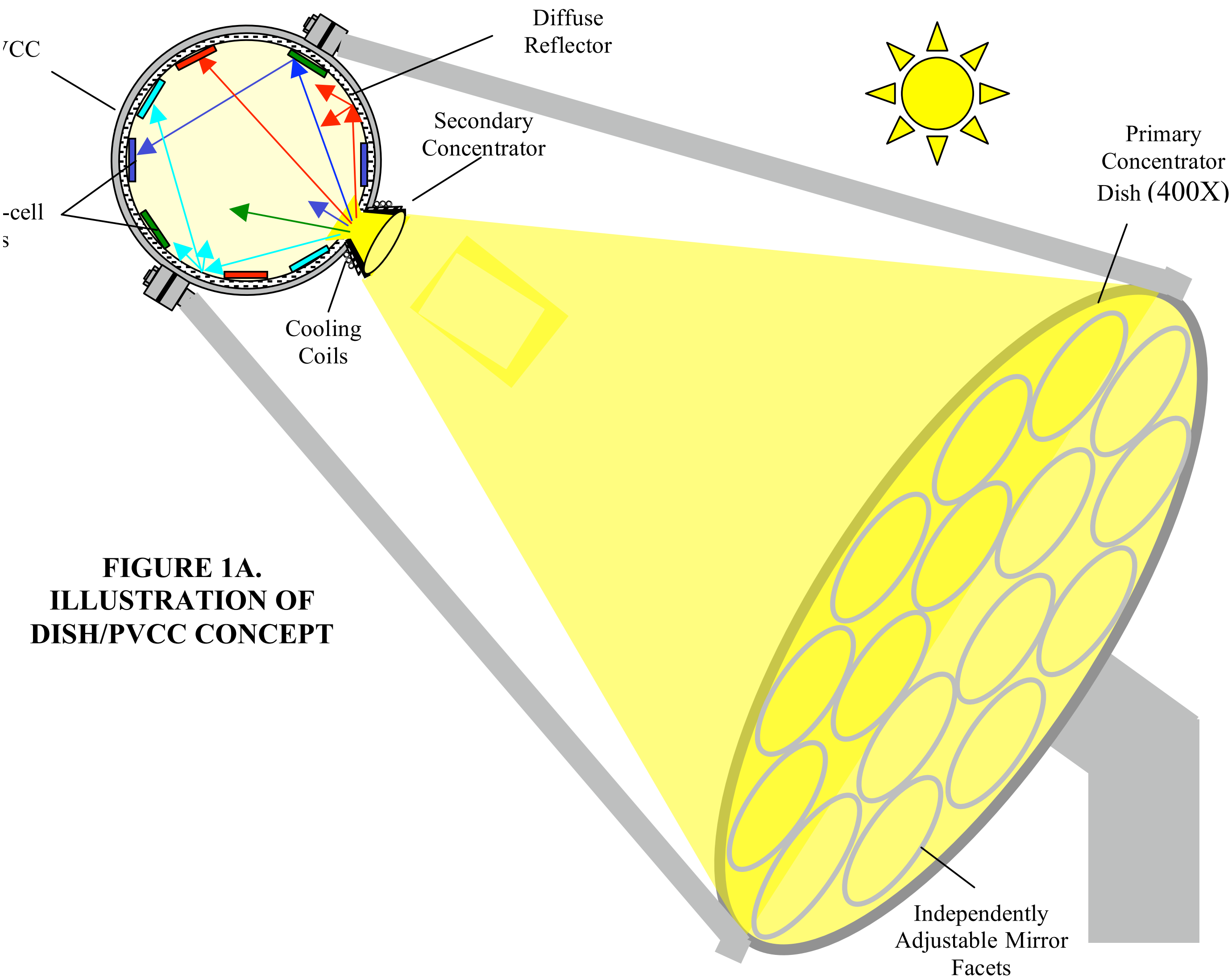


**FIGURE 1A.
ILLUSTRATION OF
DISH/PVCC CONCEPT**